CP Violation in the Standard Model Non-leptonic Decays of Charmed Mesons

Pietro Santorelli
Dipartimento di Fisica "E. Pancini"
Università di Napoli Federico II
&
INFN - Sezione di Napoli

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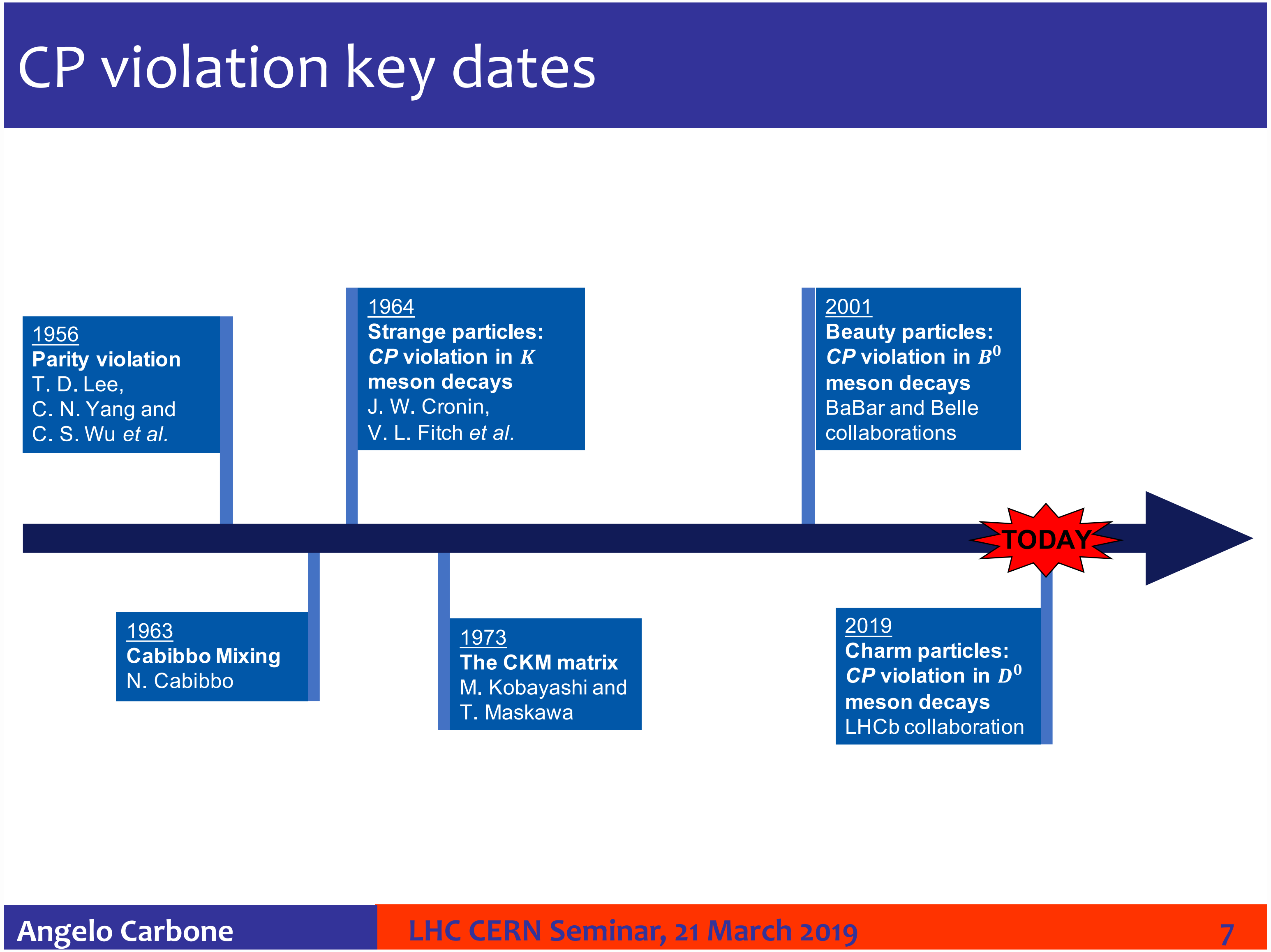
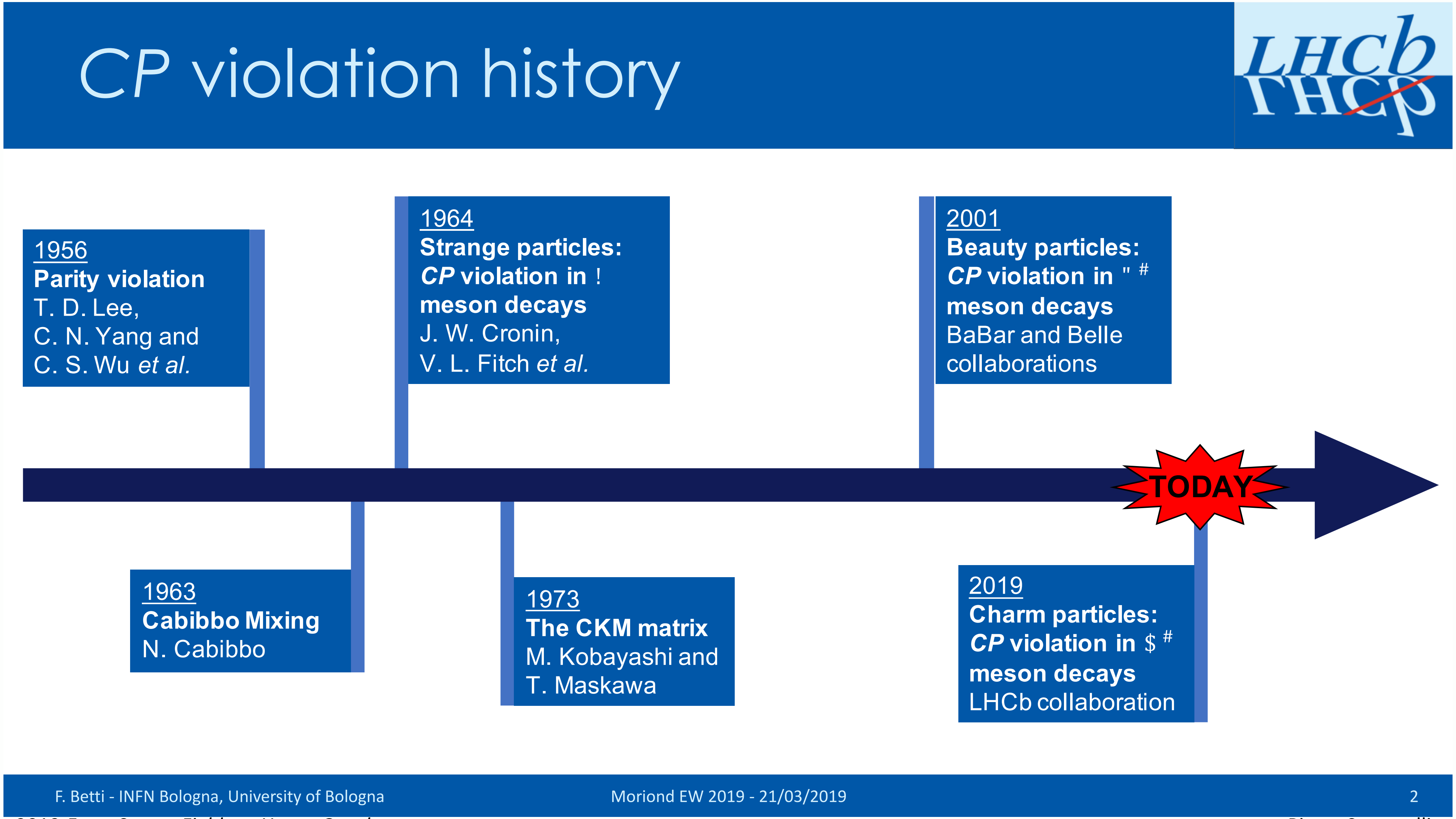
Europe/Moscow timezone

LHCb Collaboration announcement



LHCb Collaboration announcement



LHCb Collaboration announcement

Why charm is charming?

- *CP* violation in charm sector (was) not observed
- Only way to probe *CP* violation in up-type mesons
- Complementary to K and B mesons
- SM expectation lie in the range $10^{-3} - 10^{-4}$
- Intense theoretical activities since several years on this topic

(Not a complete) List of recent theoretical papers on charm physics

Golden et. al., PLB 222 (1989) 501
Bianco et al., Riv. Nuovo Cim. 26N7 (2003) 1
Grossman et al, PRD 75 (2007) 036008
Artuso et al., AR Nucl. Part. Sci. 58 (2008) 249
Khodjamirian et al., PLB 774 (2017) 235
Pirtskhalava et al. , PLB 712 (2012) 81
Cheng et al., PRD 85 (2012) 034036
Feldmann et al., JHEP 06 (2012) 007
Li et al., PRD 86 (2012) 036012
Franco et al., JHEP 05 (2012) 140
Brod et al., JHEP 10 (2012) 161
Atwood et al., PTEP 2013 (2013) 093B05
Hiller et al., PRD 87 (2013) 014024
Grossman et al., JHEP 04 (2013) 067
Müller et al., PRL 115 (2015) 251802

Angelo Carbone LHC CERN Seminar, 21 March 2019 22

What has been measured? (1/2)

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.154 \pm 0.029)\%$$

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})}$$

The LHCb Collaboration observes for the first time CP violation in charm decays with a significance of 5.3 standard deviations

What has been measured? (2/2)

The flavour of D mesons is fixed by

- The charge of slow pion in the decay $D^{*+} \to D^0\pi^+$
- The charge of the muon in the $B \to D^0\, X\, \mu^-\overline{\nu}$

A combination of the data from

- Run 2, 6 fb^{-1} @ 13 TeV
- Run 1, 3 fb^{-1} @ 7 TeV and 8 TeV

$$\Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$$

$$\Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$$

Compatible'with'previous'LHCb'results'and'the'WA

$$\Delta A_{\mathrm{CP}} = (-0.154 \pm 0.029)\%$$

A. Carbone

$$\Delta A_{CP} = (+14 \pm 16(\text{stat}) \pm 8\,(\text{syst}))\times 10^{-4}$$

μ,tagged Run 1'(3'fb,^{1})

Phys.'Rev.'Lett.'116'(2016)

$$\Delta A_{CP} = (-10 \pm 8\,(\text{stat}) \pm 3\,(\text{syst}))\times 10^{-4}$$

π,tagged Run 1'(3'fb,^{1})

JHEP'07'041'(2014)

CP Violation in the Standard Model (1/7)

I. I. Bigi, A.I. Sanda, CP Violation, Cambridge U. Press
Y. Nir, hep-ph/991132
L. Silvestrini, 1905.00798 [hep-ph]

1. The Gauge Symmetry of the Standard Model is

$$G_{\rm SM} = SU(3)_{\rm C} \times SU(2)_{\rm L} \times U(1)_{\rm Y}$$

2. Each fermion's family is classified as

$$Q^I_{Li} \equiv (3,2,+1/6), \quad u^I_{Ri} \equiv (3,1,+2/3), \quad d^I_{Ri} \equiv (3,1,-1/3),$$

$$L^I_{Li} \equiv (1,2,-1/2), \quad \ell^I_{Ri} \equiv (1,1-1)$$

3. The scalar multiplet is

$$\phi \equiv (1,2,+1/2)$$

4. Spontaneous Symmetry Breaking

$$<\phi>= \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

$$G_{\rm SM} \to SU(3)_{\rm C} \times U(1)_{\rm EM}$$

CP Violation in the Standard Model (2/7)

The Lagrangian is

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Gauge} + \mathcal{L}_{\rm Dirac} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm Yukawa}$$

$$-\frac{1}{4}F^i_{\mu\nu}F_i^{\mu\nu}$$

$$\overline{Q^I_{Li}}\; \imath\gamma^\mu D_\mu\; Q^I_{Li}$$

$$(D_\mu\phi)^\dagger(D^\mu\phi) - \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2$$

$$D^\mu = \left(\partial^\mu + \frac{i}{2}g_s G^\mu_a\lambda_a + \frac{i}{2}g W^\mu_b\tau_b + \frac{i}{6}g' B^\mu\right)$$

$$Y^d_{ij}\,\overline{Q^I_{Li}}\,\phi\, d^I_{Rj} + Y^u_{ij}\,\overline{Q^I_{Li}}\,\tilde\phi\, u^I_{Rj} + Y^\ell_{ij}\,\overline{L^I_{Li}}\,\phi\,\ell^I_{Rj} + \text{h.c.}$$

The hermiticity implies

CP

$$Y_{ij}\,\overline{\psi_{Li}}\,\phi\,\psi_{Rj} + Y^*_{ij}\,\overline{\psi_{Rj}}\,\phi^\dagger\,\psi_{Li}$$

CP

and so CP is a symmetry if

$$Y_{ij} = Y^*_{ij}$$

CP Violation in the Standard Model (3/7)

How many free parameters in the Yukawa sector?

- For any Y^f (Y^u, Y^d,Y^ℓ) we have 3x3 complex parameters → 27 complex parameters
- For any representation (if we switch off the Yukawa term)

$$G_{global}(Y=0) = U(3)^Q \times U(3)^u \times U(3)^d \times U(3)^L \times U(3)^\ell$$

and so the SM is invariant under

$$\tilde{Y}^d = V_Q^\dagger Y^d V_{\bar{d}}, \quad \tilde{Y}^u = V_Q^\dagger Y^u V_{\bar{u}}, \quad \tilde{Y}^\ell = V_L^\dagger Y^\ell V_{\bar{\ell}},$$

- The V are unitary matrices → we can use this freedom to remove 15 real and 30 imaginary parameters
- However, there is a residual symmetry in the SM when we switch on the Yukawa term

$$G_{global} = U(1)^B \times U(1)^e \times U(1)^\mu \times U(1)^\tau$$

- The residual parameters are
  - 27 - 15 = 12 reals
  - 27 - 26 = 1 phase

⇒ **This single phase is the source of CP Violation in the SM**

CP Violation in the Standard Model (4/7)

What happens if we write the SM Lagrangian in terms of mass eigenstates?

After the symmetry breaking, the Yukawa terms give rise the fermion mass terms

$$(M_d)_{ij}\overline{d^I_{Li}}d^I_{Rj} + (M_u)_{ij}\overline{u^I_{Li}}u^I_{Rj} + (M_\ell)_{ij}\overline{\ell^I_{Li}}\ell^I_{Rj} + \text{h.c.}$$

Where

$$M_f = \frac{v}{\sqrt{2}}Y^f$$

The diagonalization of the mass matrices, M, means

$$V_{fL}M_fV^\dagger_{fR} = M^{\text{diag}}_f,$$

And so the new fermion fields are given by

$$d_{Li} = (V_{dL})_{ij}d^I_{Lj} \qquad u_{Li} = (V_{uL})_{ij}u^I_{Lj}$$

The interaction charged terms are given by

$$\frac{g}{\sqrt{2}}\overline{u_{Li}}\gamma^\mu(V_{uL}V^\dagger_{dL})_{ij}d_{Lj}W^+_\mu + \text{h.c.} = \frac{g}{\sqrt{2}}(V_{CKM})_{ij}\overline{u_{Li}}\gamma^\mu W^+_\mu d_{Lj} + \text{h.c.}$$

CP Violation in the Standard Model (5/7)

The Cabibbo-Kobayashi-Maskawa matrix

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

Given that $\mathbf{s}_{13} \ll \mathbf{s}_{23} \ll \mathbf{s}_{12} \ll 1$, a perturbative expansion in powers of the sine of the Cabibbo angle $\mathbf{s}_{12}$ can be performed, defining

$$\begin{aligned} \lambda &\equiv s_{12} \\ A &\equiv s_{23}/\lambda^2 \\ (\rho + i\eta) &\equiv s_{13}e^{i\delta}/(A\lambda^3) \end{aligned}$$

$$V_{CKM} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} - \frac{\lambda^4}{8} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + A^2\lambda^5\left(\frac{1}{2} - \rho - i\eta\right) & 1 - \frac{\lambda^2}{2} - \frac{\lambda^4(1+4A^2)}{8} & A\lambda^2 \\ A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2\left(1 - \frac{\lambda^2}{2}\right) - A\lambda^4(\rho + i\eta) & 1 - \frac{A^2\lambda^4}{2} \end{pmatrix}$$

where

$$\begin{aligned} \bar{\rho} &= \rho\left(1 - \frac{\lambda^2}{2}\right) \\ \bar{\eta} &= \eta\left(1 - \frac{\lambda^2}{2}\right) \end{aligned}$$

Parameter	Value +/- Error
A	0.810 ± 0.013
λ	0.2259 ± 0.0016
$\bar{\varrho}$	0.154 ± 0.022
$\bar{\eta}$	0.342 ± 0.014

UTfit

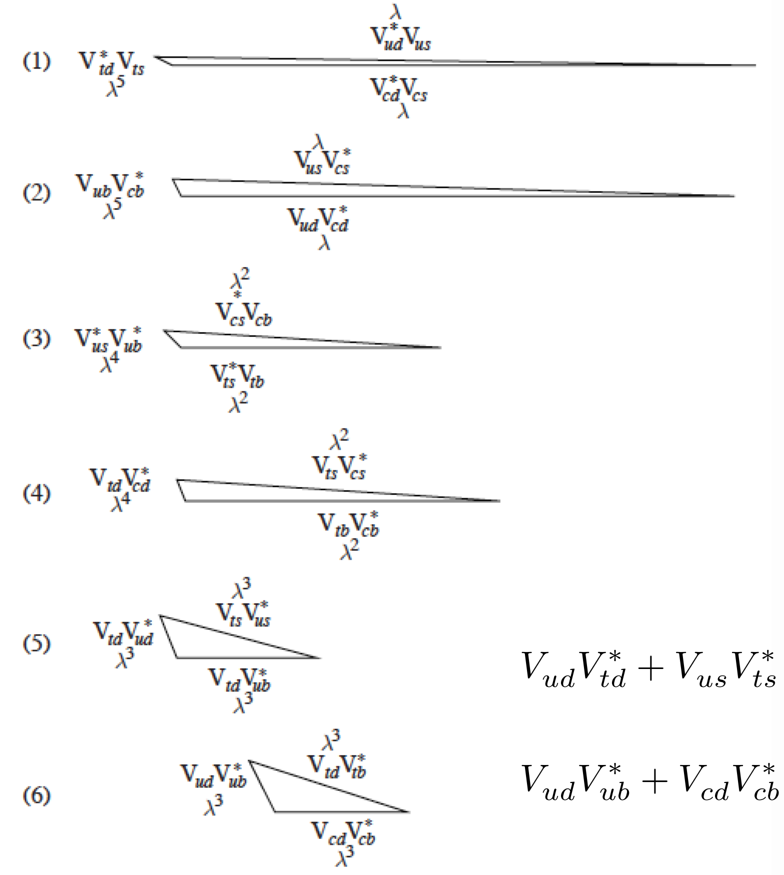
CP Violation in the Standard Model (6/7)

The Cabibbo-Kobayashi-Maskawa matrix

The unitarity of CKM matrix implies

$$\sum_{i=1}^{3} |V_{ij}|^2 = 1 \qquad j = 1,2,3.$$

$$\sum_{i=1}^{3} V_{ij}\, V_{ik}^* = 0 = \sum_{i=1}^{3} V_{ji}\, V_{ki}^* \qquad j \neq k \in \{1,2,3\}$$



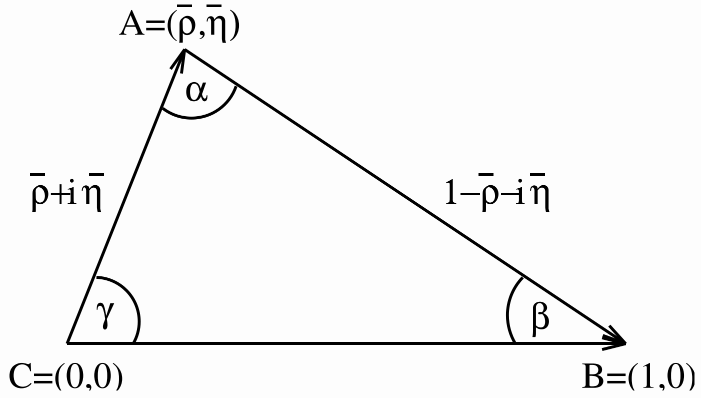
$$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} - \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = R_b e^{i\gamma} + R_t e^{-i\beta} = 1 \simeq (\overline{\rho} + i\overline{\eta}) + (1 - \overline{\rho} - i\overline{\eta})\ ,$$

$$R_b \equiv \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| \qquad R_t \equiv \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| \qquad \alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \qquad \beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$



CP Violation in the Standard Model (7/7)

In conclusion we can say that

1) The CP Symmetry is explicitely broken in the Standard Model
2) There is a single source of CP violation, the phase δ (or η)
3) The CP violation appears only in the charged current interactions of quarks
4) CP violation is closely related to flavor changing interactions

If we look at hadron’s processes we can classify the CP violation effects into three classes

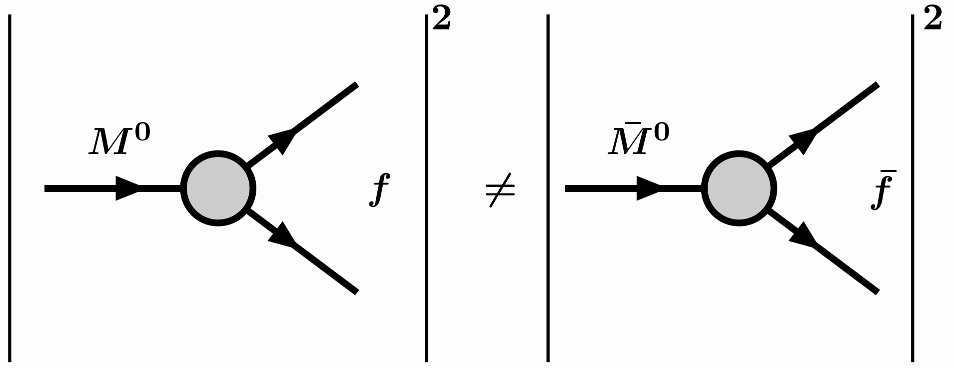
1. Direct CP Violation
2. CP Violation in the mixing
3. CP Violation in the Interference between mixing and decays

I. I. Bigi, A.I. Sanda, CP Violation, Cambridge U. Press

CP Violation in the decays: The direct CPV

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

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



$$\Delta m \approx \Delta\Gamma \approx 0$$

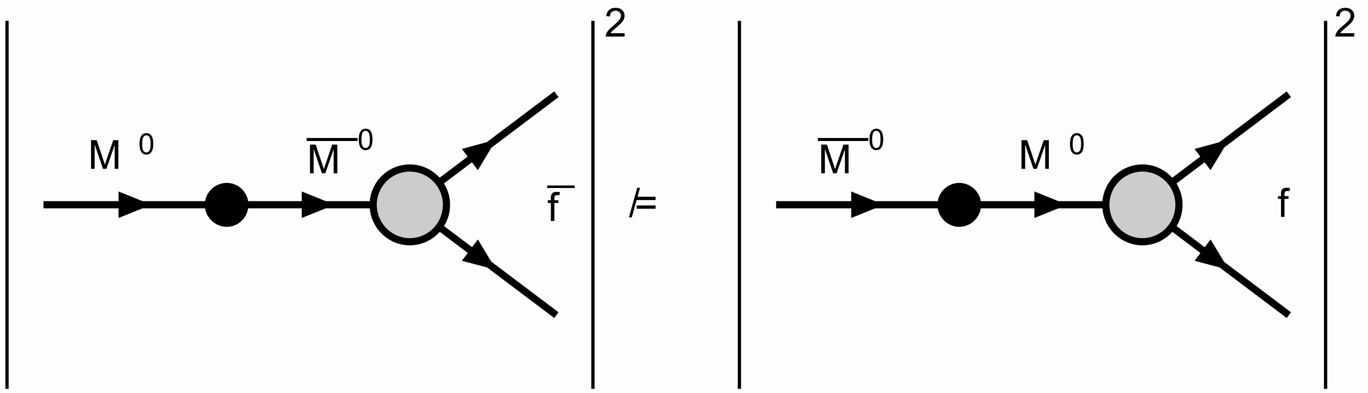
$$a_{CP}^{\mathrm{dir}} = \frac{\Gamma(M^0 \to f) - \Gamma(\bar{M}^0 \to \bar{f})}{\Gamma(M^0 \to f) + \Gamma(\bar{M}^0 \to \bar{f})}$$

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

CP Violation in the decays: The CPV in the mixing

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

$$|q| \neq |p| \qquad\qquad M^0 \to f \not\leftarrow \bar{M}^0 \quad \text{or} \quad M^0 \not\to f \leftarrow \bar{M}^0$$



This kind of CPV is of the indirect type

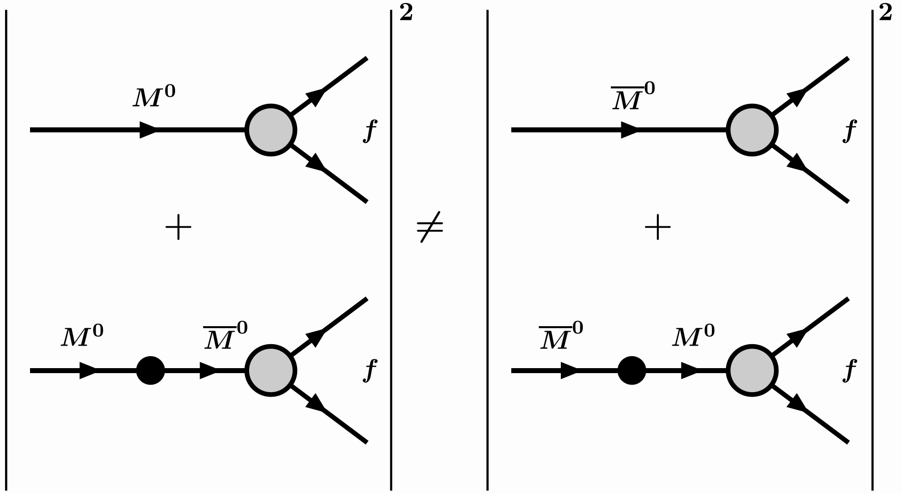
CP Violation in the decays: CPV in the interference

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

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

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

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



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

CP Symmetry if $\lambda_f = \dfrac{1}{\lambda_f} \Rightarrow \lambda_f = 1$

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

Neutral Flavored Mesons: Time Evolution (1/2)

The flavoured meson eigenstates evolve accordingly to

$$\imath\hbar\frac{d}{dt}\begin{pmatrix} M^0(t) \\ \bar{M}^0(t) \end{pmatrix} = \left(\boldsymbol{M} - \frac{\imath}{2}\boldsymbol{\Gamma}\right)\begin{pmatrix} M^0(t) \\ \bar{M}^0(t) \end{pmatrix}$$

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

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

Neutral Flavored Mesons: Time Evolution (2/2)

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

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

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

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

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

$$x = \frac{1}{\Gamma}\left[\langle \bar{D}^0 | \mathcal{H} | D^0 \rangle + \mathcal{P} \sum_n \frac{\langle D^0 | \mathcal{H} | n \rangle \langle n | \mathcal{H} | \bar{D}^0 \rangle + \langle \bar{D}^0 | \mathcal{H} | n \rangle \langle n | \mathcal{H} | D^0 \rangle}{m_D^2 - E_n^2}\right]$$

$$y = \frac{1}{2\Gamma} \sum_n \rho_n \left[\langle D^0 | \mathcal{H} | n \rangle \langle n | \mathcal{H} | \bar{D}^0 \rangle + \langle \bar{D}^0 | \mathcal{H} | n \rangle \langle n | \mathcal{H} | D^0 \rangle\right]$$

$$x, y \approx \lambda^2 [SU(3) breaking]^2$$

A.F. Falk, Y. Grossman, Z. Ligeti, and A.A. Petrov 2001

$x = (0.36^{+0.21}_{-0.16})\%$ $y = (0.67^{+0.06}_{-0.13})\%$ (HFLAV)

$\Delta A_{\rm CP}$ and $\Delta a_{\rm CP}^{\rm dir}$

$$\begin{aligned}\Delta A_{\rm CP} &= A_{\rm CP}(K^+K^-) - A_{\rm CP}(\pi^+\pi^-)\\ &\approx \Delta a_{\rm CP}^{\rm dir}\left(1+\frac{\overline{\langle t\rangle}}{\tau(D^0)}y_{\rm CP}\right)+\frac{\Delta\langle t\rangle}{\tau(D^0)}a_{\rm CP}^{\rm ind}\end{aligned}$$

$< t >_f$ is the reconstructed decay time of a given decays

$$\begin{aligned}\overline{\langle t\rangle} &= \frac{\langle t\rangle_{KK}+\langle t\rangle_{\pi\pi}}{2}\\ \Delta\langle t\rangle &= \langle t\rangle_{KK}-\langle t\rangle_{\pi\pi}\end{aligned}$$

$$\begin{aligned}\frac{\Delta\langle t\rangle}{\tau(D^0)} &= 0.115\pm0.002\\ \frac{\overline{\langle t\rangle}}{\tau(D^0)} &= 1.71\pm0.10\end{aligned}$$

$$\Delta a_{CP}^{dir} = (-0.156 \pm 0.029)\ \%$$

$$\begin{aligned}y_{\rm CP} &= (5.7\pm1.5)\times10^{-3}\\ a_{\rm CP}^{\rm ind} &= (2.8\pm2.8)\times10^{-4}\end{aligned}$$

$$\Delta A_{\rm CP} = (-0.154\pm0.029)\%$$

Direct CPV into Hadronic two body decays of D Mesons

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

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

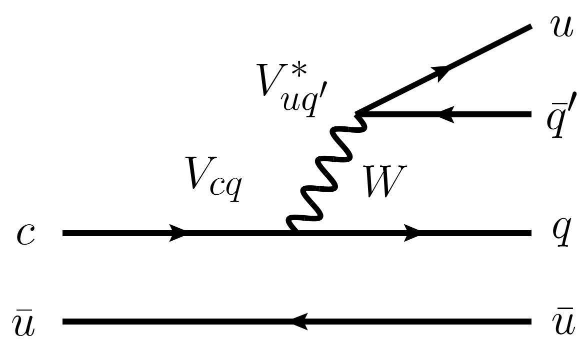
$$\bar{\mathcal{A}} = T^*\, e^{\imath\delta_T} + P^*\, e^{\imath\delta_P}$$

$$a_{\rm CP}^{\rm dir} = \frac{|\mathcal{A}|^2 - |\bar{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\bar{\mathcal{A}}|^2} = \frac{2\,\Im(T^*\,P)\ \sin(\delta_T - \delta_P)}{|T|^2 + |P|^2 + 2\,\Re(T^*\,P)\ \cos(\delta_T - \delta_P)} \approx 2\Im\left(\frac{P}{T}\right)\sin(\delta_T - \delta_P)$$

By taking into account the CKM matrix elements

$$a_{\rm CP}^{\rm dir} \approx -13\,\times\,10^{-4}\left|\frac{P}{T}\right|\sin(\delta_T - \delta_P)$$

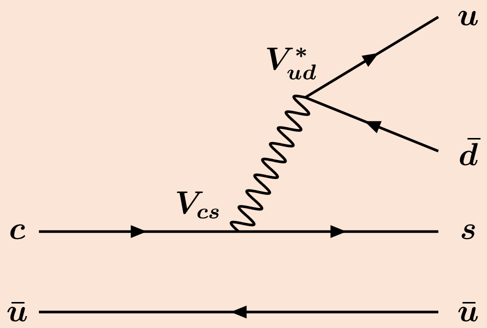
Hadronic two body decays of D Mesons



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

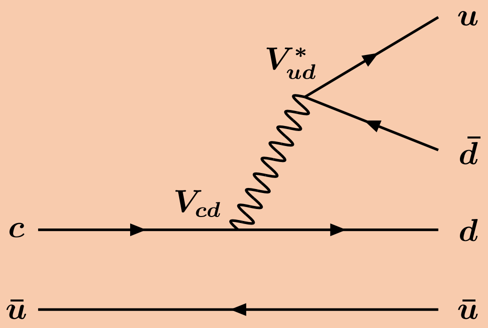
We classify the decay processes into three classes

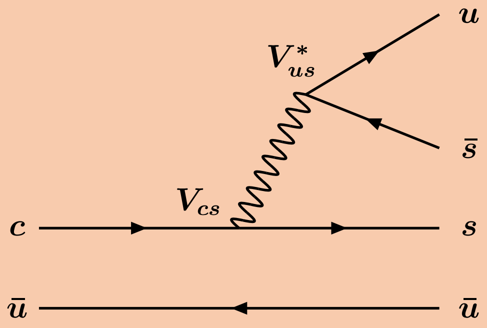
Cabibbo Favoured (**CF**)



$|V_{cs}V^*_{ud}| \approx 1 \quad (D^0 \to K^-\pi^+)$

Singly Cabibbo Suppressed(**SCS**)

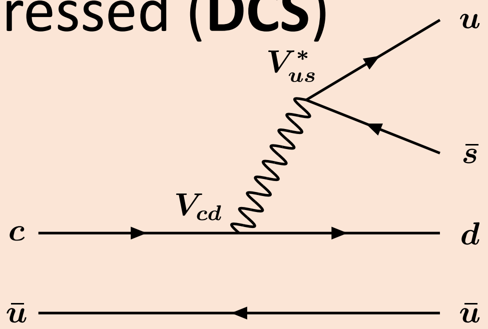




$|V_{cd}V^*_{ud}| \approx \lambda \quad (D^0 \to \pi^+\pi^-)$

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

Double Cabibbo Suppressed (**DCS**)



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

Weak effective Hamiltonian

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

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

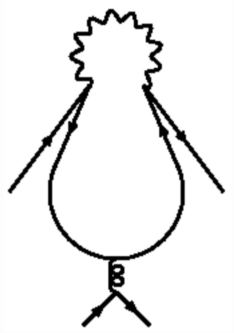
Current-Current Operators

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

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

Strong Penguin Operators

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



Hadronic Matrix Elements

We have to evaluate $\langle f | H_w | D \rangle = \frac{G_F}{\sqrt{2}} V V^* C_j \langle f | O_j | D \rangle + \ldots$

- The Wilson coefficients can be computed perturbatively
- The hadronic matrix elements are dominated by non-perturbative QCD
  - QCD factorization doesn't work well because of large Λ_{QCD}/m_c corrections
  - From first principles: Lattice QCD (medium term)
- Models can be useful to estimate order of magnitudes
  - Factorization & Final State interactions
  - Topological Amplitudes approach with/without $SU(3)_F$ (+ $1/N_c$ ..)
  - Flavor symmetries ($SU(3)_F$, Isospin, U-spin, etc…)

Possible Approaches to Direct CPV in SCS D Decays

$$a_{CP}^{dir} \approx -13 \times 10^{-4} \left|\frac{P}{T}\right| \sin(\delta_T - \delta_P)$$

$$\left|\frac{P}{T}\right|_{\pi^+\pi^-} = 0.093 \pm 0.011\,,$$

$$\left|\frac{P}{T}\right|_{K^+K^-} = 0.075 \pm 0.015\,.$$

Khodjamirian, Petrov (2017)
Chala, Lenz, Rusov, Scholtz (2019)

$$\left|a_{CP}^{dir}(D^0 \to \pi^+\pi^-)\right| \leq (1.2 \pm 0.1) \times 10^{-4}$$

$$\left|a_{CP}^{dir}(D^0 \to K^+K^-)\right| \leq (0.9 \pm 0.2) \times 10^{-4}$$

$$\left|\Delta a_{CP}^{dir}\right| \leq (2.0 \pm 0.3) \times 10^{-4}$$

New Physics

Z', Composite Higgs, Extra-dimensions…

- $|P/T|$ could be large as in the case of $\Delta I = 1/2$ in the K decays
- Final State Interactions could be large

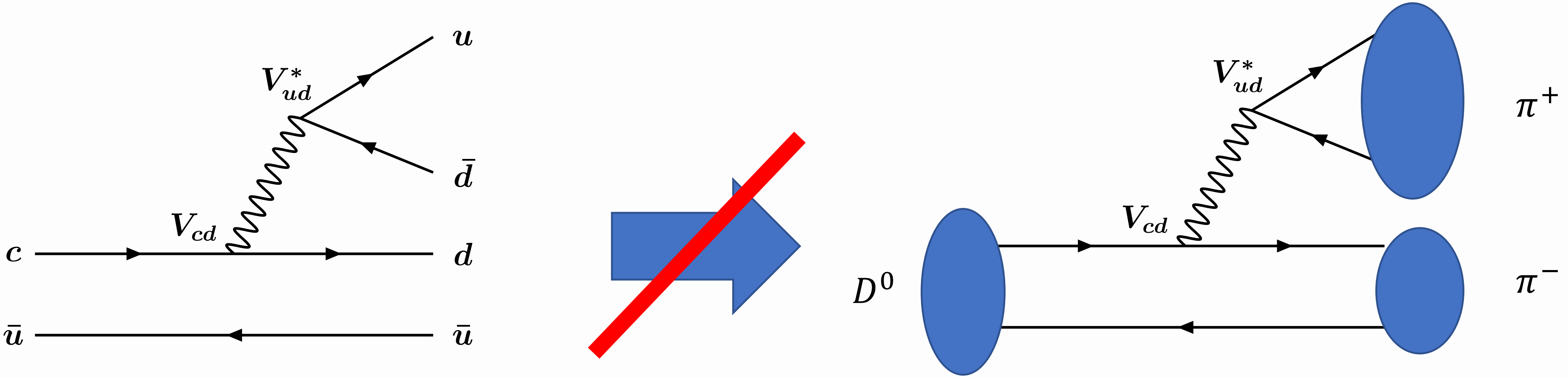
$$a_{CP}^{dir} \lesssim 10^{-2}$$

Standard Model

Golden, Grinstein (1989)
Brod, Kagan, Zupan (2012)
Brod, Grossman, Kagan, Zupan (2012)
Bhattacharya, Gronau, Rosner (2012)
Franco, Mishima, Silvestrini (2012)
Buccella, Lusignoli, Pugliese, Santorelli (2013)

Calculation of the Hadronic Amplitudes (1)

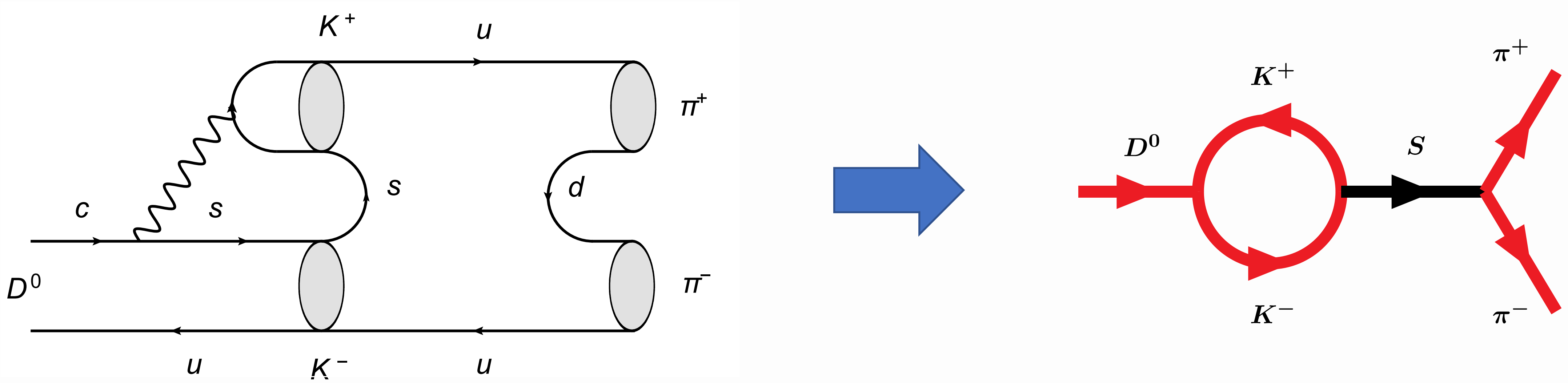
Factorization



$$\langle \pi^+\pi^- | J_\mu J^\mu | D^0 \rangle \neq \langle \pi^- | J_\mu | D^0 \rangle \langle \pi^+ | J^\mu | 0 \rangle$$

Calculation of the Hadronic Amplitudes (2)

Final State Interactions



For the Pseudoscalar-Pseudoscalar final state a scalar octect S_c with $J^P = 0^+$

- The couplings are fixed by SU(3) symmetry
- The amplitudes acquires a phase: $\tan\delta = \frac{\Gamma(S)}{2(m_S - m_D)}$

F. Buccella, M. Lusignoli, G. Miele, A. Pugliese, P.S., (1995)

Calculation of the Hadronic Amplitudes: SU(3)$_F$

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

The idea to study charmed particles by assuming SU(3)$_F$ flavour symmetry is very old and quite simple (in principle)

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

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

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

B. Grinstein and R.F. Lebed (1996)
I. Hinchliffe and T.A. Kaeding (1996)

Using Wigner-Eckart theorem we have the following Reduced Matrix Elements (RME)

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

Experimental Data and SU(3)$_F$ Symmetry

PDG 2018

$$A(D^0 \to K^+ K^-) = -A(D^0 \to \pi^+ \pi^-) \Rightarrow \begin{aligned} Br(D^0 \to \pi^+\pi^-) &= (1.407 \pm 0.025) \times 10^{-3} \\ Br(D^0 \to K^+K^-) &= (3.97 \pm 0.07) \times 10^{-3} \end{aligned}$$

$$\tan\theta_C \underbrace{A(D^+ \to \bar{K}^0\pi^+)}_{\text{CF}} = \sqrt{2}\, \underbrace{A(D^+ \to \pi^0\pi^+)}_{\text{SCS}} \Rightarrow \frac{Br(D^+ \to \pi^0\pi^+)}{Br(D^+ \to K_S\pi^+)} = \tan^2(\theta_C)\frac{PhS(D^+ \to \pi^0\pi^+)}{PhS(D^+ \to \bar{K}^0\pi^+)} = 0.057\ (0.080 \pm 0.006)$$

$$A(D^0 \to K^0\overline{K}^0) = 0 \Rightarrow Br(D^0 \to K_S K_S) = (1.70 \pm 0.12) \times 10^{-4}$$

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

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

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

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

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

SU(3) SYMMETRY BREAKING CORRECTIONS SHOULD BE INCLUDED

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

A BRUTE FORCE ANALYSIS CANNOT BE DONE

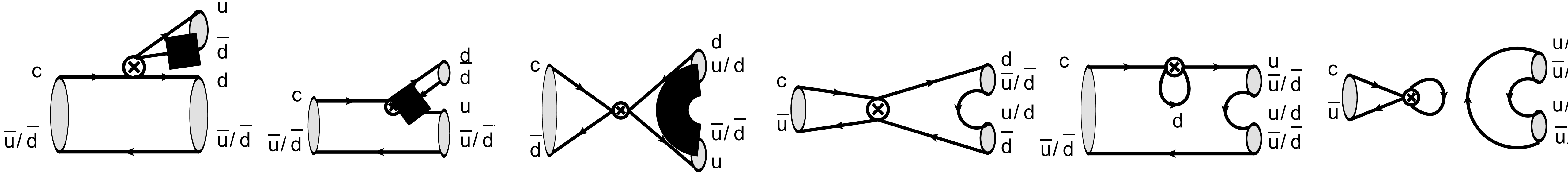
- They include in the fit the $a_{CP}^{dir}(f)$ (25 data, 25 parameters)
- The agreement with the data is good (No, assumptions)
- Very large enhancement of Penguin contributions, **3**, for large ΔA_{CP}

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

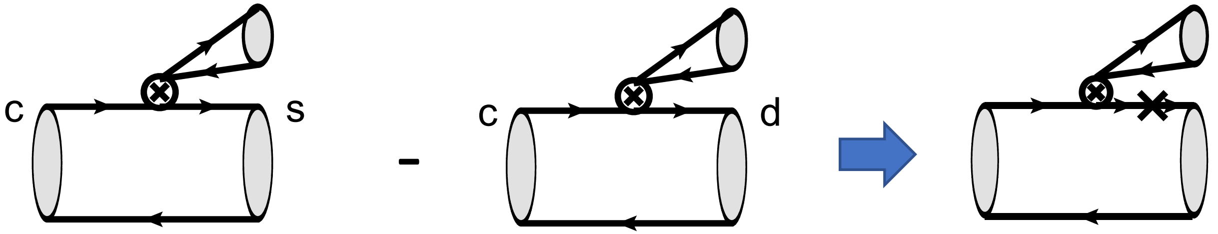
Topological Amplitudes & SU(3)$_F$ (1/2)

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

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



First order SU(3) corrections are included are included in terms of Topological Amplitudes



- $1/N_c$ counting rules: $(T, A) \sim Factorization + \delta_{T,A}$ where $\delta_{T,A} \sim 1/N_c^2$
- SU(3)-breaking corrections $< 50\%$, corrections $1/N_c^2 < 15\%$
- $\chi^2 = 0$ (# parameters > # experimental data)

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

Topological Amplitudes & SU(3)$_F$ (2/2)

Penguins and Penguins annihilations are not constrained by the experimental data on Branching ratios $Br(D \to PP)$

IT IS NOT POSSIBLE TO PREDICT CP ASYMMETRIES

But one can build combinations of CP asymmetries containing only those topological amplitudes obtained by the fit: sum rules of CP direct asymmetries

- $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$ and $D^0 \to \pi^0\pi^0$
- $D^+ \to \overline{K}^0K^+$, $D_s^+ \to K^0\pi^+$ and $D_s^+ \to K^+\pi^0$

S. M\"uller, U. Nierste, and S. Schacht (2015)

$a_{CP}^{dir}(D^0 \to K_s K_S)$ receives contribution from the Exchange (obtained in their previous paper) and Penguin Annihilation (PA) diagrams. A perturbative estimation of PA allows to give: $a_{CP}^{dir}(D^0 \to K_s K_S) \leq 1.1\%$

U. Nierste, and S. Schacht (2015)

A Simple Model for SCS Decays of D^0

F. Buccella, M. Lusignoli, A. Pugliese. , P.S., (2013)

- Amplitudes are obtained by assuming $SU(3)_F$
- FSI are responsible of $SU(3)_F$ breaking

D^0 is and U-spin (d ↔ s) singlet

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

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

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

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:

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

A Model for all $D_{(s)}$ -> PP (1/2)

F. Buccella, M. Lusignoli, A. Pugliese, P.S. (2013)
F. Buccella, A. Paul, P.S. (2019)

- More parameters to take into account CF and DCS of D^0 and D^+ and D_s decays and $SU(3)_F$ breaking
- For the FSI the phase corresponding to the state **(8, I=1/2)** should be included

	$\mu \pm \sigma$		$(\mu \pm \sigma)$	
T	0.424 ± 0.003	δ_0	-2.373 ± 0.062	2.373 ± 0.062
C	-0.211 ± 0.003	δ_0'	-0.840 ± 0.046	0.840 ± 0.046
κ	-0.036 ± 0.004	$\delta_{\frac{1}{2}}$	-1.632 ± 0.020	1.632 ± 0.020
κ'	-0.063 ± 0.088	δ_1	-1.085 ± 0.038	1.085 ± 0.039
K	0.100 ± 0.012			
K'	-0.153 ± 0.072			
Δ	-0.026 ± 0.019			
ϕ	0.435 ± 0.025		-1.897 ± 0.211	-0.465 ± 0.211
ϵ_δ	0.067 ± 0.061			

$\Delta a_{CP}^{dir} = (-0.164 \pm 0.028)$ % (HFLAV WA)

A Model for all $D_{(s)}$ -> PP (2/2)

F. Buccella, M. Lusignoli, A. Pugliese, P.S. (2013)
F. Buccella, A. Paul, P.S. (2019)

SCS

Channel	Fit ($\times 10^{-3}$)	PDG ($\times 10^{-3}$)	BESIII ($\times 10^{-3}$)
$D^0 \to \pi^+\pi^-$	1.448 ± 0.019	1.407 ± 0.025	1.508 ± 0.028
$D_0^+ \to \pi^0\pi^0$	0.816 ± 0.025	0.822 ± 0.025	–
$D^+ \to \pi^+\pi^0$	1.235 ± 0.033	1.17 ± 0.06	1.259 ± 0.040
$D^0 \to K^+K^-$	4.064 ± 0.044	3.97 ± 0.07	4.233 ± 0.067
$D^0 \to K_S K_S$	0.168 ± 0.012	0.17 ± 0.012	–
$D^+ \to K^+ K_S$	3.164 ± 0.056	2.83 ± 0.16	3.183 ± 0.067
$D^+ \to K^+ K_L$	3.164 ± 0.056	–	3.21 ± 0.16
$D_s^+ \to \pi^0 K^+$	1.41 ± 0.15	0.63 ± 0.21	–
$D_s^+ \to \pi^+ K_S$	1.24 ± 0.06	1.22 ± 0.06	–

CA & DCS

Channel	Fit ($\times 10^{-3}$)	PDG ($\times 10^{-3}$)	BESIII ($\times 10^{-3}$)
$D^+ \to \pi^+ K_S$	15.80 ± 0.29	14.7 ± 0.8	15.91 ± 0.31
$D^+ \to \pi^+ K_L$	14.37 ± 0.52	14.6 ± 0.5	–
$D^0 \to \pi^+ K^-$	38.96 ± 0.32	38.9 ± 0.4	–
$D^0 \to \pi^0 K_S$	12.29 ± 0.21	11.9 ± 0.4	12.39 ± 0.28
$D^0 \to \pi^0 K_L$	9.73 ± 0.21	10.0 ± 0.7	–
$D_s^+ \to K^+ K_S$	14.67 ± 0.41	15.0 ± 0.5	–
$D^+ \to \pi^0 K^+$	0.151 ± 0.013	0.181 ± 0.027	0.231 ± 0.022
$D^0 \to \pi^- K^+$	0.141 ± 0.003	0.1385 ± 0.0027	–
$D^0 \to \pi^\pm K^\mp$	39.1 ± 0.32	–	38.98 ± 0.52

a_{CP}^{dir} Predictions

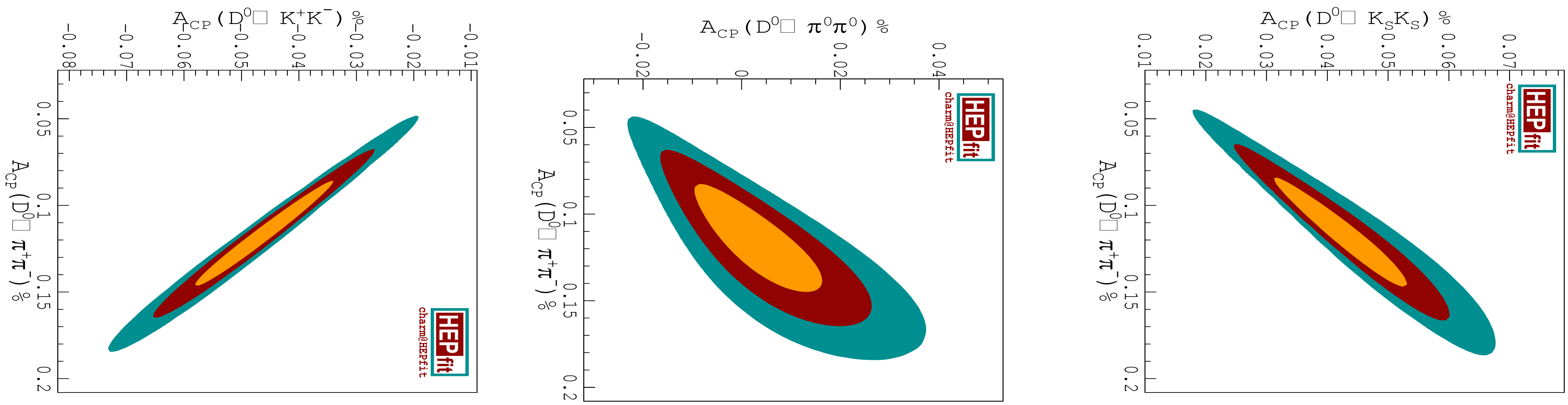
F. Buccella, A. Paul, P.S., (2019)

a_{CP}^{dir}	$(\mu \pm \sigma)$ (%)		a_{CP}^{dir}	$(\mu \pm \sigma)$ (%)	
	$\delta_i \to$ -ve	$\delta_i \to$ +ve		$\delta_i \to$ -ve	$\delta_i \to$ +ve
$D^0 \to \pi^+\pi^-$	0.117 ± 0.020	0.118 ± 0.020	$D^+ \to K^+K_S$	-0.028 ± 0.005	-0.026 ± 0.005
$D^0 \to \pi^0\pi^0$	0.004 ± 0.009	0.079 ± 0.010	$D_s^+ \to \pi^+K_S$	-0.040 ± 0.007	-0.036 ± 0.007
$D^0 \to K^+K^-$	-0.047 ± 0.008	-0.046 ± 0.008	$D_s^+ \to \pi^0K^+$	0.048 ± 0.006	-0.003 ± 0.004
$D^0 \to K_SK_S$	0.043 ± 0.007	0.038 ± 0.007			

LHCb measurement implies that all the asymmetries in theTable are non-zero with a significance of greater than of 5σ with the exception of $D^0 \to \pi^0\pi^0$

a_{CP}^{dir} Correlations

F. Buccella, A. Paul, P.S., (2019)



Correlations between asymmetries. The orange, red and green regions are the 68%, 95% and 99% probability regions respectively.

Conclusions

- LHCb experiment observes for the first time the CP Violation in charm decays with a significance of 5.3 standard deviations
- The result $\Delta a_{CP}^{dir} = (-0.156 \pm 0.029)\ \%$ is compatible with the (order of magnitude) predictions of theoretical models in the framework of the Standard Model
- Measurements of CP asymmetries will help us to check/improve reliability of our models
- A lot of theoretical work should be done for calculations from first principles