CPV IN D-\bar{D} MIXING

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- Introduction
- Present status
- Future prospects
- Conclusions

Based on Grossman, Kagan, Ligeti, Perez, Petrov & L.S., shamefully still in preparation...
INTRODUCTION

- CP violation in $\Delta F=2$ processes is the most sensitive probe of NP, reaching scales of $O(10^5)$ TeV
- CPV in D mixing gives best bound after $\varepsilon_K$
- How did we get there? How far can we go?

UTfit @ EPS2015
D MIXING

- **D mixing is described by:**
  - **Dispersive D → D̄ amplitude** $M_{12}$
    - **SM:** long-distance dominated, not calculable at present (see however progress in $\Delta m_K$)
    - **NP:** short distance, calculable w. lattice
  - **Absorptive D → D̄ amplitude** $\Gamma_{12}$
    - **SM:** long-distance, not calculable
    - **NP:** negligible
  - **Observables:** $|M_{12}|$, $|\Gamma_{12}|$, $\Phi_{12} = \text{arg}(\Gamma_{12} / M_{12})$
\[ \text{Use CKM unitarity} \]
\[ V_{cd} V_{ud}^* + V_{cs} V_{us}^* + V_{cb} V_{ub}^* = \lambda_d + \lambda_s + \lambda_b = 0 \]

\[ \text{eliminate } \lambda_d \text{ and take } \lambda_s \text{ real (all physical results convention independent)} \]

\[ \text{imaginary parts suppr. by } r = \text{Im } \frac{\lambda_b}{\lambda_s} = 6.5 \times 10^{-4} \]

\[ M_{12}, \Gamma_{12} \text{ have the following structure:} \]
\[ \lambda_s^2 (f_{dd} + f_{ss} - 2f_{ds}) + 2\lambda_s \lambda_b (f_{dd} - f_{ds} - f_{db} + f_{sb}) + O(\lambda_b^2) \]
GIM ⇔ SU(3) (U-spin)

- Write long-distance contributions to $M_{12}$ and $\Gamma_{12}$ in terms of U-spin quantum numbers:

$$\lambda_s^2 (\Delta U=2) + \lambda_s \lambda_b (\Delta U=2 + \Delta U=1) + O(\lambda_b^2)$$

$$\sim \lambda_s^2 \varepsilon^2 + \lambda_s \lambda_b \varepsilon$$

- CPV effects at the level of $r/\varepsilon \sim 2 \times 10^{-3} \sim 1/8^\circ$ for “nominal” SU(3) breaking $\varepsilon \sim 30\%$
“REAL SM” APPROXIMATION

- Given present experimental errors, it is perfectly adequate to assume that SM contributions to both $M_{12}$ and $\Gamma_{12}$ are real.
- All decay amplitudes relevant for the mixing analysis can also be taken real.
- NP could generate a nonvanishing phase for $M_{12}$. 

LHCb Implications 3/11/15  
L. Silvestrini
“REAL SM” APPROXIMATION II

- Define $|D_{S,L}| = p|D^0| \pm q|D^0|$ and $\delta = (1-|q/p|^2)/(1+|q/p|^2)$. All observables can be written in terms of $x = \Delta m/\Gamma$, $y = \Delta \Gamma/2\Gamma$ and $\delta$, with $\Delta m \sim 2|M_{12}| + O(\sin^2 \Phi_{12})$, $\Delta \Gamma \sim 2|\Gamma_{12}| + O(\sin^2 \Phi_{12})$ and $\delta \sim 2|M_{12}| |\Gamma_{12}| \sin \Phi_{12}/(4|M_{12}|^2 + |\Gamma_{12}|^2) + ...$

- Notice that $\phi = \text{arg}(q/p) = \text{arg}(y + i \delta x) - \text{arg}^{12}_{12}$

- $|q/p| \neq 1 \iff \phi \neq 0$ clear signals of NP

Ciuchini et al; Kagan & Sokoloff
**CPV IN MIXING TODAY**

- latest UTfit average (HFAG very similar):

\[
x = (3.5 \pm 1.5) \times 10^{-3}, \quad y = (5.8 \pm 0.6) \times 10^{-3},
\]

\[
|q/p|^{-1} = (0.7 \pm 1.8) \times 10^{-2},
\]

\[
\phi = \arg(q/p) = (-0.21 \pm 0.57)^\circ
\]
CPV IN MIXING TODAY II

- The corresponding results on fundamental parameters are

\[ |M_{12}| = (4.3 \pm 1.8)/\text{fs}, \quad |\Gamma_{12}| = (14.1 \pm 1.4)/\text{fs} \]

and \[ \Phi_{12} = (0.8 \pm 2.6)^\circ \ ([-5.8,8.8]^\circ \ @ \ 95\%) \]
FUTURE PROSPECTS

• Belle II and LHCb upgrade will considerably improve the sensitivity to CPV in charm mixing

• Should critically re-examine the statement of negligible CPV in the SM:
  - Could CPV amplitudes be dynamically enhanced?
  - Is the SU(3)/U-spin argument reliable?
BEYOND THE “REAL SM”

- Relax the assumption of real $\Gamma_{12}$, introduce $\phi_{\Gamma_{12}} = \text{arg } \Gamma_{12}$

- The relation between $\phi$, $x$, $y$ and $\delta$ is modified as follows:

  $$\phi = \text{arg}(q/p) = \text{arg}(y+i\delta x) - \phi_{\Gamma_{12}}$$

- How large can $\phi_{\Gamma_{12}}$ be in the SM?

- Can we extract $\phi_{\Gamma_{12}}$ from experimental data?
In principle, if decay amplitudes are not real, they affect the extraction of $\phi$:

$$\phi \rightarrow \phi + \delta \phi_f,$$

with $\delta \phi_f = \arg(\bar{A}_f/A_f)$ (f CP eig.)

- for CA and DCS decays, $\delta \phi_f$ negligible
- for SCS decays, $\delta \phi_f = A_{CP}^{\text{dir}} (D \rightarrow f) \cot \delta_f$
  ($\delta_f$ strong phase difference, expected $O(1)$)
- present data on DCPV imply $\delta \phi_f \sim 10^{-3}$
BEYOND THE "REAL SM" IV

- CPV contributions to $\phi_{\Gamma 12}$ are enhanced by $1/\varepsilon$, while this is not the case for $\delta \phi_f$

- can go beyond the "real SM" approximation by adding one universal phase $\phi_{\Gamma 12}$ and fitting for $\phi_{12}$ and $\phi_{\Gamma 12}$ or, equivalently, for $\phi_{M12}$ and $\phi_{\Gamma 12}$
CAN WE ESTIMATE $\phi_{\Gamma_{12}}$ IN SM?

- $\Gamma_{12} = \Gamma_{12}^0 + \delta\Gamma_{12} = \lambda_s^2 (\Delta U=2) + \lambda_s \lambda_b (\Delta U=2 + \Delta U=1) + O(\lambda_b^2) \sim \lambda_s^2 \Gamma_5 + \lambda_s \lambda_b \Gamma_3$

- $\Gamma_5$ changes U-spin by 2 units, arises @ $O(\varepsilon^2)$

- $\Gamma_3$ changes U-spin by one unit, arises @ $O(\varepsilon)$

- Trade $\Gamma_{12}^0$ for $\gamma \Gamma$, get

  $\phi_{\Gamma_{12}} \sim \text{Im} \lambda_s \lambda_b / \gamma \Gamma_3 / \Gamma \sim 5 \times 10^{-3} \Gamma_3 / \Gamma$
CHARM CPV @ LHCb UPGRADE

- Expected errors w. LHCb upgrade:
  - $\delta x=1.5 \times 10^{-4}$, $\delta y=10^{-4}$, $\delta |q/p|=10^{-2}$, $\delta \phi=3^\circ$ (from $K_s\pi\pi$); $\delta y_{CP}=\delta A_\Gamma=4 \times 10^{-5}$ (from $K^+K^-$)
- Allows to experimentally determine $\phi_{\Gamma_{12}}$ with a reach on CPV @ the degree level:
  - $\delta \phi_{M_{12}} = \pm 1^\circ$ (17 mrad) and $\delta \phi_{\Gamma_{12}} = \pm 2^\circ$ (34 mrad) @ 95% prob.
  - $\Lambda>10^5$ TeV
CHARM CPV @ HI-LUMI

- **XFX: “Extreme” flavour experiment (LHCb upgrade L x 100)**

- **Naive extrapolation, scaling LHCb upgrade estimates:**

  - $\delta x = 1.5 \times 10^{-5}$, $\delta y = 10^{-5}$, $\delta |q/p| = 10^{-3}$, $\delta \phi = .3^\circ$ (from $K_s\pi\pi$); $\delta y_{CP} = \delta A_\Gamma = 4 \times 10^{-6}$ (from $K^+K^-$)

  - $\delta \phi_{M12} = \pm 0.1^\circ$ (1.7 mrad) and $\delta \phi_{\Gamma 12} = \pm 0.2^\circ$ (3.4 mrad) @ 95% prob.

  - $\Lambda > 3 \times 10^5$ TeV, close to the bound from $\epsilon_K$

see e.g. talk by G. Punzi @ 1st Future Hadron Collider Workshop
CONCLUSIONS

• Given present experimental errors, SM contributions to CPV in mixing-related observables can be safely neglected, yielding a constrained three-parameter fit ($M_{12}$, $\Gamma_{12}$, $\phi_{12}$) which allows to probe NP at the % level.

• Future experimental improvements will however go well below the % level, reaching a level in which SM CPV contributions might be non-negligible.
CONCLUSIONS II

- Given the SU(3) structure of $\Delta c = 1$ and $\Delta c = 2$ amplitudes, CPV contributions to $\Gamma_{12}$ are parametrically enhanced over CPV contributions to decay amplitudes.

- Generalizing the fit introducing $\phi_{\Gamma_{12}}$ captures dominant SM effects.

- LHCb upgrade will probe $\phi_{M_{12}}$ and $\phi_{\Gamma_{12}}$ at the level of $1^\circ$, while XFX could reach $0.1^\circ$ hitting the SM expectation.
BACKUP SLIDES
ESTIMATING $\Gamma_3/\Gamma$

- $\Gamma_3$ generated by SCS decay amplitudes

- two-body decays account for 75% of hadronic D decays, with PP~VV~AP~PV/3

- use exp data on BR's and DCPV to perform SU(3) analysis and estimate $\Gamma_3$

- Wait for lattice progress on nonleptonic two-body D decays...
ESTIMATING $\Gamma_3/\Gamma$ II

- Analysis of U-spin amplitudes suggests that currently $\Gamma_3/\Gamma \sim 1$ is plausible, and also that $\phi_{\Gamma_{12}}/\delta \phi_f \sim 4$, as previously argued, yielding

  $$\phi_{\Gamma_{12}} \sim 5 \text{ mrad (0.3°)}$$

  and leaving plenty of room for NP

- More data, in particular for PV SCS decays, would allow for a better estimate of $\phi_{\Gamma_{12}}$

- $\phi_{M_{12}}$ might be estimated via dispersion rel.
U-spin structure of $\Delta C = 1$ Hamiltonian

$$H_1 : \Delta U = 1 \text{ triplet } \propto \bar{c}u \ (\bar{d}s, \bar{s}s - \bar{d}d, \bar{s}d)$$

$$H_0 : \Delta U = 0 \text{ singlet } \propto \bar{c}u \ (ss + \bar{d}d)$$

Possible final state $U$-spin quantum numbers

triplet $f_1 \ (U = 1, U_3 = 0, \pm 1)$, singlet $f_0 \ (U = 0, U_3 = 0)$

$\bar{D}^0 \rightarrow PP$ example, with CP eigenstates:

$$f_1 = \frac{K^+K^- - \pi^+\pi^-}{\sqrt{2}}, \ K^+\pi^-, \ K^-\pi^+; \quad f_0 = \frac{K^+K^- + \pi^+\pi^-}{\sqrt{2}}$$

$\bar{D}^0 \rightarrow VP$ example, non-CP eigenstates ($\bar{D}^0 \rightarrow f_1, f_0; \ \bar{f}_1, \bar{f}_0$):

$$f_1 = \frac{K^{*+}K^- - \rho^+\pi^-}{\sqrt{2}}, \ K^{*+}\pi^-, \ K^-\rho^+; \quad f_0 = \frac{K^{*+}K^- + \rho^+\pi^-}{\sqrt{2}}$$

$$\bar{f}_1 = \frac{K^{*-}K^+ - \rho^-\pi^+}{\sqrt{2}}, \ K^+\rho^-, \ K^{*-}\pi^+; \quad \bar{f}_0 = \frac{K^{*-}K^+ + \rho^-\pi^+}{\sqrt{2}}$$

Courtesy of A. Kagan
there are two decay amplitudes at 0th order in $SU(3)$ breaking, where $|0\rangle$ is U-spin singlet $D^0$:

$$t_0[f_1] \propto \langle f_1 | H_1 | 0 \rangle, \quad p_0[f_0] \propto \langle f_0 | H_0 | 0 \rangle$$

there are three decay amplitudes at 1st order in $SU(3)$ breaking, $O(\epsilon)$:

$$s_1[f_0] \propto \langle f_0 | (H_1 \times M_\epsilon)_0 | 0 \rangle, \quad t_1[f_1] \propto \langle f_1 | (H_1 \times M_\epsilon)_1 | 0 \rangle, \quad p_1[f_1] \propto \langle (f_1 \times M_\epsilon)_0 | H_0 | 0 \rangle$$

$M_\epsilon$ is the U-spin breaking "spurion"

- $M_\epsilon$ connects $\Delta U = 1$ operator $H_1$ with singlet $f_0$ final state, and $\Delta U = 0$ operator $H_0$ with triplet final state $f_1$

amplitudes for CP conjugate final states (non-CP eigenstates):

$$t_0[f_1], \quad p_0[f_0]; \quad s_1[f_0], \quad t_1[f_1], \quad p_1[f_1]$$

Courtesy of A. Kagan
The SCS decay amplitudes to $O(\epsilon)$, for $f_1$, $f_0$ final states ($U_3 = 0$),

$$\sqrt{2}A(\bar{D}^0 \rightarrow f_0) = (\lambda_s - \lambda_d) s_1[f_0] \epsilon - \lambda_b \ 2 p_0[f_0] + O(\epsilon^2)$$

$$\sqrt{2}A(\bar{D}^0 \rightarrow f_1) = (\lambda_s - \lambda_d) t_0[f_1] - \lambda_b \ p_1[f_1] \epsilon + O(\epsilon^2)$$

and similarly for $\bar{D}^0 \rightarrow \bar{f}_0, \bar{f}_1$

The CF/DCS decay amplitudes, for $f_1$ final states ($U_3 = \pm 1$)

$$A_{CF}(\bar{D}^0 \rightarrow f_1) = V_{cs} V_{ud}^* (t_0[f_1] - \frac{1}{2} t_1[f_1] \epsilon)$$

$$A_{DCS}(\bar{D}^0 \rightarrow f_1) = V_{cd} V_{us}^* (t_0[f_1] + \frac{1}{2} t_1[f_1] \epsilon)$$

and similarly for $\bar{D}^0 \rightarrow \bar{f}_1$

the $\epsilon$'s are “factored out” to keep track of orders in U-spin breaking. Thus nominally

$$t_0 \sim p_0 \sim s_1 \sim p_1 \sim t_1$$

Courtesy of A. Kagan
Expressed as exclusive sums over all decays, obtain

$$\frac{\Gamma_3}{\Gamma} = -\frac{\sum_{f_{CP}} \Gamma_3(f_{CP}) + \sum_{f, \bar{f}} \Gamma_3(f, \bar{f})}{\sum_{f_1, f_{CP}} |t_0[f_1]|^2 + \sum_{f_1, \bar{f}_1} (|t_0[f_1]|^2 + |t_0[\bar{f}_1]|^2) + O(\epsilon)}$$

where

$$\Gamma_3(f_{CP}) = 4 \text{Re}(p_0^*[f_0] s_1[f_0] \epsilon) + 2 \text{Re}(t_0^*[f_1] p_1[f_1] \epsilon)$$

$$\Gamma_3(f, \bar{f}) = 4 \text{Re}(p_0^*[f_0] s_1[\bar{f}_0] \epsilon) + 4 \text{Re}(p_0^*[\bar{f}_0] s_1[f_0] \epsilon) + 2 \text{Re}(t_0^*[f_1] p_1[\bar{f}_1] \epsilon) + 2 \text{Re}(t_0^*[\bar{f}_1] p_1[f_1] \epsilon)$$

information about the amplitude ratios

$$\frac{s_0[f_0] \epsilon}{t_0[f_1]}, \quad \frac{p_0[f_0]}{t_0[f_1]}$$

follows from branching ratio and direct CP asymmetry measurements

as more of these ratios are constrained, our knowledge of how large $|\Gamma_3|/\Gamma$ can reasonably be will improve

Courtesy of A. Kagan