CP violation in $D - \overline{D}$ mixing

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Based on Yuval Grossman, A. K., Zoltan Ligeti, Luca Silvestrini, Gilad Perez, Alexey Petrov,

in preparation

Plan

- Introduction
  - Absorptive and dispersive contributions to mixing and CP violation (CPV)
  - Phenomenology of CPV in mixing
- Today: the “superweak limit” - a constrained fit
  - parametrization of indirect CPV with one universal weak phase
- Future: departure from the superweak limit
  - two universal weak phases (absorptive and dispersive) suffice
- How large can indirect CPV be in the SM?

Introduction

Introduction

- In the SM, CP violation (CPV) in mixing enters at $O(V_{cb}V_{ub}/V_{cs}V_{us}) \sim 10^{-3}$, due to weak phase γ

- In view of current and future (LHCb, Belle II; HL-LHC?) improvements in CPV mixing measurements, this statement needs to be sharpened

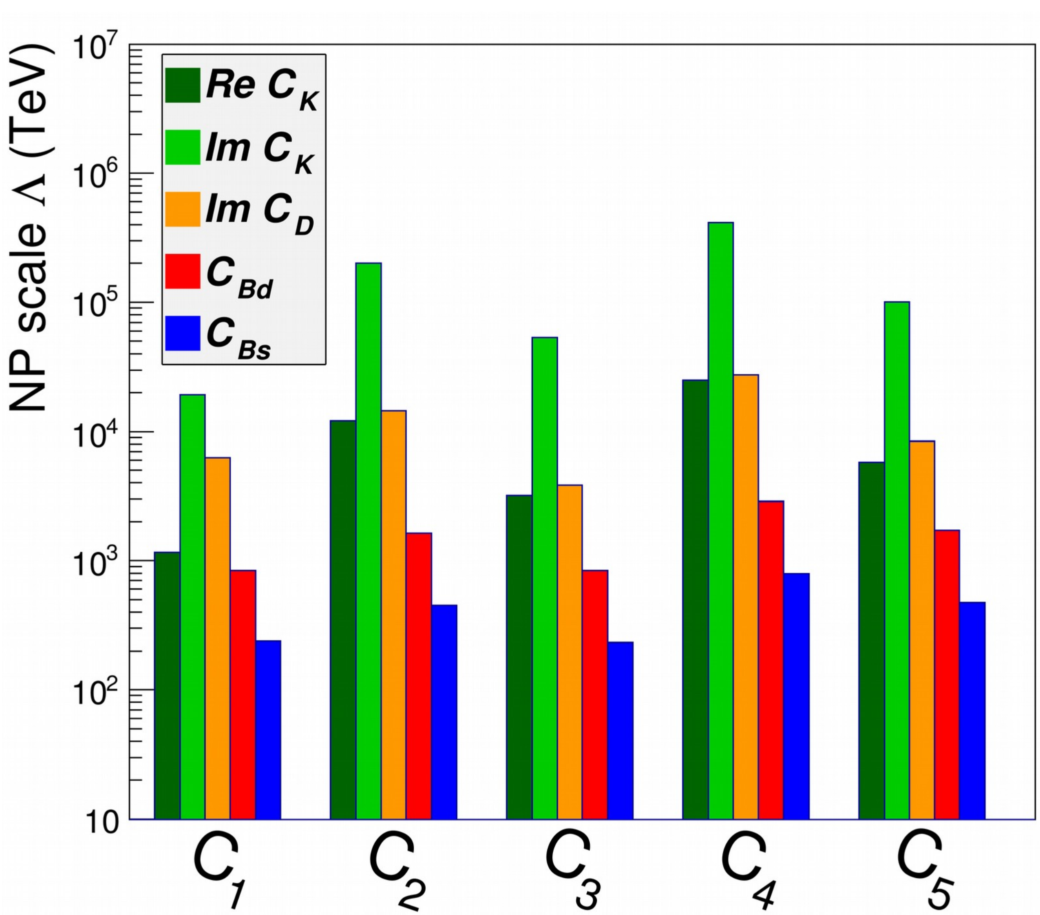
  - how large is the QCD uncertainty?

    - this has implications for how we should parametrize CPV in mixing

- how large is the current window for New Physics (NP) in mixing CPV?

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 ε_K
- How far can we push it?

Review of formalism for CPV in mixing:

- Mixing of strong interaction eigenstates $\bar{D}^0$, D^0 due to transition amplitudes

$$\langle D^0|H|\overline{D^0}\rangle = M_{12} - \frac{i}{2}\Gamma_{12}\,, \quad \langle \overline{D^0}|H|D^0\rangle = M_{12}^* - \frac{i}{2}\Gamma_{12}^*$$

- D meson mass eigenstates,

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$

  - CP conserving observables

$$x = \frac{m_2 - m_1}{\Gamma}, \qquad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

- M_{12} is dispersive mixing: due to long-distance exchange of off-shell intermediate states; and short-distance effects
  - long distance dominates in SM
  - significant short distance effect would be new physics (NP)

- Γ_{12} is absorptive mixing: due to long distance exchange of on-shell intermediate states

$$\Gamma_{12} \cong \sum_f \langle\, D^0 \,|\, H_W \,|\, f \rangle \,\langle\, f \,|\, H_W \,|\, \overline{D}^0 \rangle$$

- The “theoretical" mixing parameters

$$x_{12} \;\equiv\; 2|M_{12}|/\Gamma, \qquad y_{12} \;\equiv\; |\Gamma_{12}|/\Gamma, \qquad \phi_{12} \;\equiv\; \arg(M_{12}/\Gamma_{12})$$

  - Relations to CP conserving observables:

$$|x| = x_{12} + O(\mathrm{CPV}^2), \qquad |y| = y_{12} + O(\mathrm{CPV}^2)$$

- CPV in mixing via Γ_{12} and via long distance part of M_{12} requires subleading decay amplitudes containing weak phases:
  - SM: $V_{cb}V_{ub}^*$ suppressed amplitudes containing $e^{i\gamma}$
  - NP: subleading decay amplitudes with new weak phases
- assume only singly Cabibbo suppressed (SCS) decays contribute
  - CF/DCS contributions negligible in SM
  - NP with non-negligible DCPV in DCS/CF decays, which evades ϵ_K bounds, must be extremely exotic   Bergmann, Nir

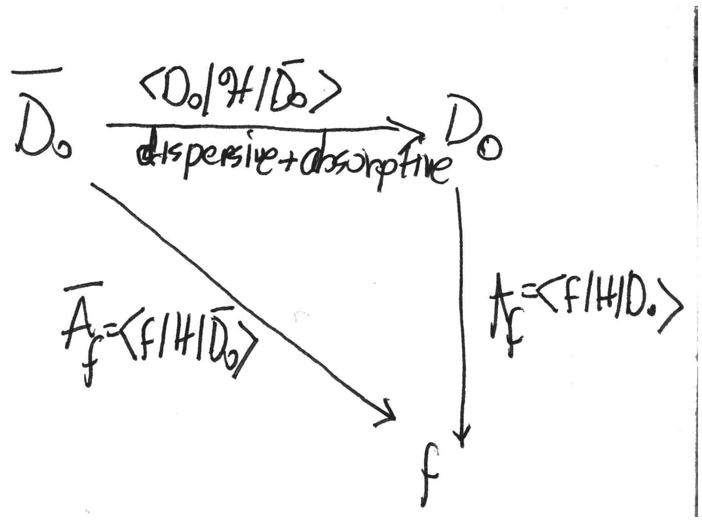
Two kinds of indirect CPV

- CPVMIX: CPV in pure mixing due to $\phi_{12} \neq 0 \Rightarrow$ interference between the dispersive and absorptive mixing amplitudes

$$\phi_{12} \neq 0 \quad \Rightarrow \quad \left|\frac{q}{p}\right| \neq 1$$

e.g., a non-vanishing semileptonic CP asymmetry, $A_{\rm SL} \propto \sin\theta_{12}$

- CPVINT: CP violation in the interference of decays with and without mixing



- CPVINT observable for CP eigenstate final state, $f = \bar{f}$:

$$\phi_{\lambda_f} = \arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right)$$

- CPVINT observable pairs for non-CP eigenstate final states, $f \neq \bar{f}$:

$$\phi_{\lambda_f} = \arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right), \quad \phi_{\lambda_{\bar{f}}} = \arg\left(\frac{q}{p}\frac{\bar{A}_{\bar{f}}}{A_{\bar{f}}}\right)$$

- $\phi_{\lambda_f}, \phi_{\lambda_{\bar{f}}} \neq 0 \quad \Rightarrow$ CPVINT time-dependent CP asymmetries, e.g. in
  - SCS decays (A_Γ): $D^0(t) \to K^+K^-\,,\ \pi^+\pi^- \neq \bar{D}^0(t) \to K^+K^-\,,\ \pi^+\pi^-$
  - DCS decays: $D^0(t) \to K^+\pi^- \neq \bar{D}^0(t) \to K^-\pi^+$
  - these asymmetries contain both CPVMIX and CPVINT contributions

The superweak limit

CPVINT in the "superweak" limit

- neglect effects of subleading decay weak phases in indirect CPV: $O(x\, A^{\rm d}_{\rm CP},\, y\, A^{\rm d}_{\rm CP})$, where $A^{\rm d}_{\rm CP}$ is the direct CP asymmetry
  - suppressed by x, y
  - $A^{\rm d}_{\rm CP}$ CKM suppressed in SM
  - allowing for NP in SCS decays, $A^{\rm d}_{\rm CP}$ bounds $\Rightarrow$ this is still an excellent approximation compared to current experimental indirect CPV errors

- in time-integrated CP asymmetries both indirect and direct CPV contribute
  - keep leading direct CPV contribution $A^{\rm d}_{\rm CP}$
  - neglect subleading direct CPV effects entering the indirect CPV contribution

- in the superweak limit $\phi_{12} \neq 0$ is dispersive, entirely due to short-distance NP in M_{12} (SM short-distance is negligible)

$$\phi_{12} = \phi^M_{12}\ , \qquad \phi^\Gamma_{12} = 0$$

- ϕ_{12} is only source of CPVINT, which is universal
  - $\phi_{\lambda_f} \to \phi$, universal CPVINT
  - CPVINT and CPVMIX related: Ciuchini et al ’07; Grossman, Perez, Nir ’09; A.K., Sokoloff ’09

$$\tan 2\phi \approx -\frac{x_{12}^2}{x_{12}^2 + y_{12}^2} \sin 2\phi_{12}$$

$$\tan \phi \approx \left(1 - \left|\frac{q}{p}\right|\right) \frac{x}{y}$$

$$\text{e.g.,} \quad \Delta Y_f = -A_\Gamma = -x_{12} \sin \phi_{12}$$

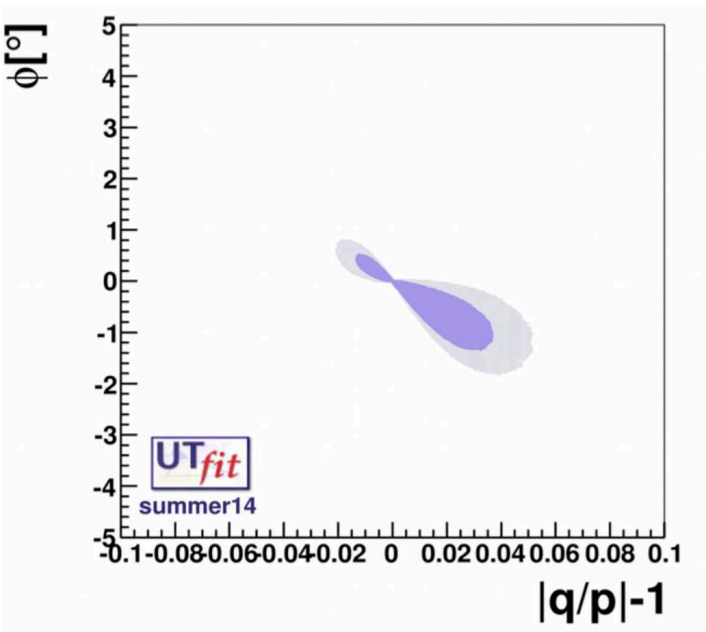
- with only one CPV phase ϕ_{12} controlling all indirect CPV, superweak fits to CPV data are much more constrained than fits in which ϕ and $|q/p|$ are independent
  - fits assume no direct CPV in doubly Cabibbo suppressed (DCS) decays $D^0 \to K^+\pi^-$

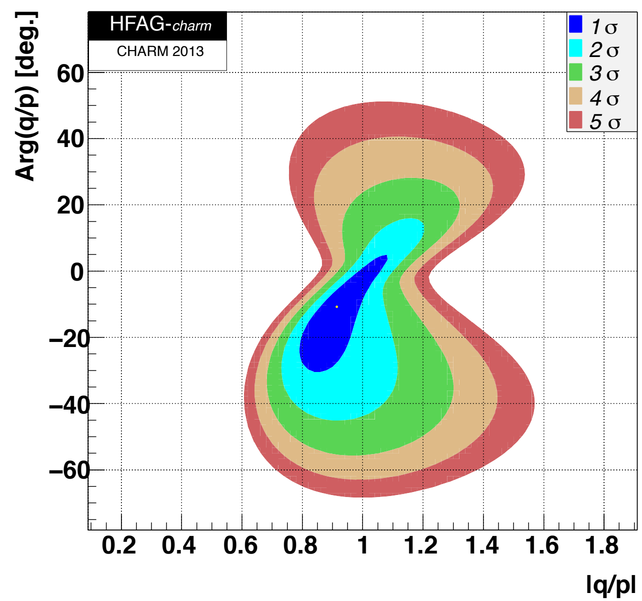
- Fit results:

$$\text{HFAG, NEW}: \quad \phi_{12}\ [\text{rad}] = 0.017^{+0.035}_{-0.03} \quad (1\sigma); \quad [-0.05, +0.14] \quad 95\%\,\text{cl}$$

$$\text{UTfit}: \quad \phi_{12}\ [\text{rad}] = 0.003 \pm 0.03 \quad (1\sigma); \quad [-0.07, +0.21] \quad 95\%\,\text{cl}$$

- ϕ vs $|q/p|$ in superweak fit vs. fit with independent $|q/p|$, ϕ





Departure from the superweak limit

Departure from the superweak limit

- we are transitioning to the $< 10\%$ era on ϕ_{12}
- at the coming level of precision, will the superweak limit continue to be a good approximation?
- what is the best way to parametrize deviations from the superweak limit?
- how large can the SM contribution to indirect CPV be?

- most general final-state specific parametrization: physical absorptive and dispersive contributions to ϕ_{12}
  - $f = CP$ eigenstate:

$$\phi^M_{12\,f} \equiv \frac{1}{2}\arg\left[\frac{M_{12}}{M^*_{12}}\left(\frac{A_f}{\overline{A}_f}\right)^2\right], \quad \phi^\Gamma_{12\,f} \equiv \frac{1}{2}\arg\left[\frac{\Gamma_{12}}{\Gamma^*_{12}}\left(\frac{A_f}{\overline{A}_f}\right)^2\right]$$

$$\text{CPVMIX} \;\; \phi_{12} = \phi^M_{12\,f} - \phi^\Gamma_{12\,f}$$

  - non-CP eigenstates f, $\bar{f}$:

$$\phi^M_{12\,f} \equiv \frac{1}{2}\arg\left[\frac{M_{12}}{M^*_{12}}\frac{A_f A_{\bar{f}}}{\overline{A}_f \overline{A}_{\bar{f}}}\right], \quad \phi^\Gamma_{12\,f} \equiv \frac{1}{2}\arg\left[\frac{\Gamma_{12}}{\Gamma^*_{12}}\frac{A_f A_{\bar{f}}}{\overline{A}_f \overline{A}_{\bar{f}}}\right]$$

$$\text{CPVMIX} \;\; \phi_{12} = \phi^M_{12\,f} - \phi^\Gamma_{12\,f}$$

Beyond superweak with a universal parametrization

- in general,

$$M_{12} = M_{12}^0 + \delta M_{12,\mathrm{SM}} + \delta M_{12,\mathrm{NP}}, \quad \Gamma_{12} = \Gamma_{12}^0 + \delta\Gamma_{12,\mathrm{SM}} + \delta\Gamma_{12,\mathrm{NP}}$$

$$M_{12}^0,\ \Gamma_{12}^0 \propto (\lambda_s - \lambda_d)^2; \quad \delta M_{12,\mathrm{SM}},\ \delta\Gamma_{12,\mathrm{SM}} \propto (\lambda_s - \lambda_d)\lambda_b$$

(in superweak $\delta M_{12,\mathrm{SM}} = \delta\Gamma_{12} = 0$)

- define "theoretical" phase convention independent universal CPV phases

$$\phi_{12}^\Gamma \equiv \arg\left(\frac{\Gamma_{12}}{\Gamma_{12}^0}\right), \quad \phi_{12}^M \equiv \arg\left(\frac{M_{12}}{M_{12}^0}\right), \quad \phi \equiv \arg\left(\frac{q}{p}\frac{1}{\Gamma_{12}^0}\right)$$

- $\arg(\Gamma_{12}^0) = \arg(M_{12}^0) = \arg[(\lambda_s - \lambda_d)^2]$ provides a "reference ruler" for the no CPV direction in the complex plane

- ϕ_{12}^Γ takes into account the weak phases of the subleading amplitudes in all decays

Define the misalignment between the general parametrization and the “theoretical" universal phases

$$\delta\phi_f \equiv \phi^{\Gamma}_{12\,f} - \phi^{\Gamma}_{12} = \phi^{M}_{12\,f} - \phi^{M}_{12} = \phi - \phi_{\lambda_f}$$

- in CF/DCS decays with no NP, the misalignment is known and negligible,
  e.g., in CPVINT in $D^0 \to K^{\pm}\pi^{\mp}$, $D^0 \to K_S\pi^+\pi^-$

$$\phi_{\lambda_f} = \phi, \quad \phi^{\Gamma}_{12\,f} = \phi^{\Gamma}_{12}, \quad \phi^{M}_{12\,f} = \phi^{M}_{12}$$

- $\delta\phi_f$ is related to direct CPV: $\delta\phi_f = A^{\rm dir}_{CP}(D \to f)\,\cot\delta$, δ is a strong phase
  - $D^0 \to K^+K^-, \pi^+\pi^-$: $A^{\rm dir}_{CP} \lesssim \text{few} \times 10^{-3}$ $\Rightarrow$ $\delta\phi_f \lesssim \text{few} \times 10^{-3}$

    $\Rightarrow$ small misalignment compared to expected BelleII/LHCb sensitivity:
    $\delta\phi \approx 3^\circ \approx 0.05$ [rad]

- In general, in SM: $\phi_{12}^{\Gamma} = O(1/\epsilon)$, $\epsilon \sim 0.2$ characterizes nominal U-spin breaking

$$\Rightarrow \quad \frac{\delta\phi_f}{\phi_{12}^{\Gamma}} = O(\epsilon) \text{ in SCS } \mathrm{D}^0 \text{ decays}$$

yielding parametric suppression of misalignment relative to ϕ_{12}^{Γ}

- therefore, for expected Belle/LHCb sensitivity, can account for deviation from superweak limit with only one additional universal CPV phase beyond ϕ_{12}, e.g. ϕ_{12}^{Γ}

- fit mixing data to ϕ_{12}^{Γ} and ϕ_{12} or, equivalently, ϕ_{12}^{M} and ϕ_{12}^{Γ}
  - in practice, equivalent to "traditional" two parameter fit for ϕ, $|q/p|$l
  - back to a less constrained fit, but Belle/LHCb improved sensitivity will overcome this

Examples

- Time-dependent CPV in $D^0 \to K_S \pi^+ \pi^-$, assuming no NP in CF/DCS, yields a measurement of x, y, $|q/p|$, ϕ: ($|x| = x_{12}$, $|y| = y_{12}$)

  - use the relations

$$\left|\frac{q}{p}\right| - 1 \approx \frac{|x||y|}{x^2 + y^2} \sin \phi_{12}$$

$$\tan 2(\phi + \phi_{12}^{\Gamma}) \approx -\frac{x^2}{x^2 + y^2} \sin 2\phi_{12}$$

$$\phi_{12} = \phi_{12}^{M} - \phi_{12}^{\Gamma}$$

  to obtain the fundamental dispersive and absorptive universal phases ϕ_{12}^{M}, ϕ_{12}^{Γ}

- Time-dependent CP asymmetry in SCS decays to a CP eigenstate,

$$A_{\Gamma} = -\Delta Y_f \approx |x| \sin \phi_{12}^{M},$$

  analogous relation holds for $D^0 \to K_S \pi^+ \pi^-$ time-integrated, time-dependent CP asymmetries: $\propto \sin \phi_{12}^{M}$

CHARM CPV @ LHCb UPGRADE

- Expected errors w. LHCb upgrade:
  - $\delta x=1.5\ 10^{-4}$, $\delta y=10^{-4}$, $\delta|q/p|=10^{-2}$, $\delta\phi=3°$ (from $K_s\pi\pi$); $\delta y_{CP}=\delta A_\Gamma=4\ 10^{-5}$ (from K^+K^-)
- Allows to experimentally determine $\phi_{\Gamma 12}$ with a reach on CPV @ the degree level:
  - $\delta\phi_{M12} = \pm\ 1°$ (17 mrad) and $\delta\phi_{\Gamma 12} = \pm\ 2°$ (34 mrad) @ 95% prob.
  - $\Lambda>10^5$ TeV

- Another example: time-integrated tagged, untagged CP asymmetries for DCS/CF decays, e.g. $f = K^+\pi^-$, $\bar{f} = K^-\pi^+$

$$A_{\rm CP}^{\rm tag,\,DCS\,(CF)} \equiv \frac{\int dt(\Gamma[D^0(t)\to\bar{f}(f)] - \Gamma[\bar{D}^0(t)\to f(\bar{f})])}{\int dt(\Gamma[D^0(t)\to\bar{f}(f)] + \Gamma[\bar{D}^0(t)\to f(\bar{f})])}$$

$$A_{\rm CP}^{\rm untag} \equiv \frac{\int dt(\Gamma[D^0(t)\to\bar{f}] + \Gamma[D^0(t)\to f] - \Gamma[\bar{D}^0(t)\to\bar{f}] - \Gamma[\bar{D}^0(t)\to f])}{\int dt(\Gamma[D^0(t)\to\bar{f}] + \Gamma[D^0(t)\to f] + \Gamma[\bar{D}^0(t)\to\bar{f}] + \Gamma[\bar{D}^0(t)\to f])}$$

For $R_f \equiv |\bar{A}_f^{\rm DCS}/A_f^{\rm CF}|$, and Δ_f the strong phase between DCS and CF, obtain

$$\frac{A_{\rm CP}^{\rm tag,\,CF}}{R_f} + R_f A_{\rm CP}^{\rm tag,\,DCS} = -2|x|\sin\phi_{12}^M \cos\Delta_f$$

$$\frac{1+R_f^2}{R_f} A_{\rm CP}^{\rm untag} = \frac{A_{\rm CP}^{\rm tag,\,CF}}{R_f} - R_f A_{\rm CP}^{\rm tag,\,DCS} = -2|y|\sin\phi_{12}^\Gamma \sin\Delta_f$$

- analogous relations hold for time-dependent CP asymmetries in SCS decays to non-CP eigenstates, e.g. $D^0 \to \rho\pi,\ K^*K$, with $R_f \equiv |A_{\bar{f}}/A_f| = O(1)$ and $A_{\rm CP}^{\rm tag,\,CF\,(DCS)} \to \Delta Y_{f\,(\bar{f})}$

How large can indirect CPV be in the SM?

U-spin decomposition of Γ_{12} and M_{12} in the SM

- using CKM unitarity,

$$\Gamma_{12} = \frac{(\lambda_s - \lambda_d)^2}{4}\,\Gamma_5 + \frac{(\lambda_s - \lambda_d)\lambda_b}{2}\,\Gamma_3 + \frac{\lambda_b^2}{4}\,\Gamma_1$$

$$M_{12} = \frac{(\lambda_s - \lambda_d)^2}{4}\,M_5 + \frac{(\lambda_s - \lambda_d)\lambda_b}{2}\,M_3 + \frac{\lambda_b^2}{4}\,M_1$$

- $\Gamma_{5,3,1},\quad M_{5,3,1}$ are $\Delta U_3 = 0$ elements of U-spin multiplets, e.g.

$$\Gamma_5 = \Gamma_{ss} + \Gamma_{dd} - 2\Gamma_{sd} \;\sim\; (\bar{s}s - \bar{d}d)^2 \;\Rightarrow\; \Delta U = 2\;\;(5\,\text{plet}) \;\Rightarrow\; O(\epsilon^2),\;\text{CF/DCS/SCS}$$

$$\Gamma_3 = \Gamma_{ss} - \Gamma_{dd} \;\sim\; (\bar{s}s - \bar{d}d)(\bar{s}s + \bar{d}d) \;\Rightarrow\; \Delta U = 1\;\;(3\,\text{plet}) \;\Rightarrow\; O(\epsilon),\;\text{SCS}$$

- $\Gamma_{12}^0 \propto \Gamma_5,\quad M_{12}^0 \propto M_5$ are CP conserving $\Rightarrow$ $y_{12},\; x_{12}$ or $y,\; x$
- $\delta\Gamma_{12} \propto \Gamma_3,\quad \delta M_{12} \propto M_3$ $\Rightarrow$ CPV via $\gamma = \arg(\lambda_b)$
- neglect $O(\lambda_b^2)$ effects of $\Gamma_1,\, M_1$

- the U-spin decomposition yields the rough estimate

$$\phi_{12}^{\Gamma} \equiv \arg\left(\frac{\Gamma_{12}}{\Gamma_{12}^{0}}\right) \approx \mathrm{Im}\left(\frac{2\lambda_b}{\lambda_s - \lambda_d}\frac{\Gamma_3}{\Gamma_5}\right) \sim \left|\frac{\lambda_b}{\theta_c}\right| \sin\gamma \times \frac{1}{\epsilon}$$

and similarly for ϕ_{12}^{M}

  - “nominal” U-spin breaking,

$$\epsilon \sim 0.2 \quad \Rightarrow \quad \phi_{12}^{\Gamma} \sim \phi_{12}^{M} \sim 3 \times 10^{-3}$$

    compared to $\phi_{12} \in [-0.07, +0.08]$ (HFAG), $[-0.07, +0.21]$ (UTfit) at 95% c.l. from “superweak” fit

- allowing for large uncertainty in this estimate, current CPV measurements $\Rightarrow$ $O(10)$ window for NP

A more refined analysis of ϕ_{12}^{Γ} in the SM

- in ϕ_{12}^{Γ} trade $\Gamma_5 \cong \Gamma_{12}^0$ for $y \times \Gamma$
  - shifts explicit ϵ dependence from $1/\epsilon \to \epsilon$, because $y = O(1/\epsilon^2)$, $\Gamma_3 = O(\epsilon)$

$$|\phi_{12}^{\Gamma}| = \left|\frac{\sin\gamma\ \lambda_b\,(\lambda_s - \lambda_d)}{2y}\right| \quad \frac{|\Gamma_3|}{\Gamma} \approx 0.005\frac{|\Gamma_3|}{\Gamma}$$

  where $\Gamma_3 = O(\epsilon)$, and is due to SCS decays:

$$\Gamma_3 = \frac{2}{(\lambda_s - \lambda_d)\lambda_b} \sum_f A(\bar{D}^0 \to f)_{\rm SCS}\ \ A^*(D^0 \to f)_{\rm SCS}$$

- consider U-spin decomposition of the SCS and CF decay amplitudes
  - two-body decays account for $\approx 75\%$ of all hadronic D^0 decays, with $D^0 \to VP,\ VV,\ PP,\ AP$ accounting for $\approx 33\%,\ 12\%,\ 12\%,\ 12\%$, respectively (Cheng, Chiang)
  - comparison of $D^0 \to VP,\ VV,\ PP,\ AP$ branching ratios, direct CP asymmetries with U-spin decompositions could tell us how large a $|\Gamma_3|/\Gamma$ ratio is plausible

- currently,

$$\frac{|\Gamma_3|}{\Gamma} \sim 1 \;\Rightarrow\; \phi_{12}^{\Gamma} \sim 0.005$$

is plausible, consistent with our more naive estimate

- for $\delta\phi_f$ in SCS decays, this yields

$$\left|\frac{\phi_{12}^{\Gamma}}{\delta\phi_f}\right| = \left|\frac{\lambda_s^2 \sin\gamma}{2y}\right| \frac{1}{\mathrm{Re}(r_f)} \frac{|\Gamma_3|}{\Gamma} \sim \frac{\lambda_s^2}{2y} \approx 4,$$

consistent with the $\delta\phi_f/\phi_{12}^{\Gamma} = O(\epsilon)$ parametric suppression
- r_f is the ratio of subleading to leading $D^0 \to f$ decay amplitudes, $r_f \sim P/T \sim 1$

- improved precision, particularly for $A_{\rm CP}^{\rm d}(D^0 \to VP)$ and ${\rm Br}(D^0 \to VP)$ modes will be most welcome, since VP modes are expected to contribute substantially to Γ_3 (based on their relative importance in Γ)

this would allow a sharper comparison of prominent U-spin amplitudes in Γ_3 and Γ

Conclusion

- we are transitioning to a very exciting period for CPV in $D - \overline{D}$ mixing
- currently we have an $O(10)$ window to NP
- we have introduced a new universal parametrization that captures the departure from the superweak limit at a level of precision that is appropriate for the sensitivity expected in the next generation experiments at LHCb, Belle II
  - it requires one additional universal phase, e.g. ϕ_{12}^{Γ}
  - final state specific phases associated with direct CPV are not required, in the absence of a surprisingly large $A_{\mathrm{CP}}^{\mathrm{dir}}$ measurement
- If there is NP in CPV, it is almost certainly short distance in ϕ_{12}^{M}
  - the parametrization allows separate measurements of ϕ_{12}^{M} and ϕ_{12}^{Γ}

- mapping out the branching ratios and direct CP asymmetries in a large number of D^0 decay modes is important
  - this will directly impact our understanding of how large absorptive CPV in mixing can be in the SM, with our current estimate being $\phi^{\Gamma}_{12} = O(0.005)$
  - it could also help us further understand how large the dispersive SM contribution (ϕ^M_{12}) could be, by relating it to the absorptive one using dispersion relations - more challenging
  - a simple U-spin based estimate yields $\phi^M_{12} \sim \phi^{\Gamma}_{12}$
- In the Belle II / LHCb era we roughly expect

$$\delta\phi^M_{12} \approx 0.017, \quad \delta\phi^{\Gamma}_{12} \approx 0.034 \quad @95\%\text{c.l.}$$

  to be compared with the current window
  $\phi_{12} \in\in [-0.07, +0.08]\ (\text{HFAG, new});\ [-0.07, +0.21]\ (\text{UTfit})\ 95\%\ \text{c.l.}$
  (current errors on ϕ^M_{12}, ϕ^{Γ}_{12} are much larger) and $\phi^M_{12} \sim \phi^{\Gamma}_{12} = O(0.005)$ in SM
- at HI- LUMI (LHCb $\times$ 100) would be sensitive to SM indirect CPV

Backup slides on U-spin decomposition

- 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

$$\text{triplet } \ f_1 \ (U = 1, U_3 = 0, \pm 1), \qquad \text{singlet } \ f_0 \ (U = 0, U_3 = 0)$$

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

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

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

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

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

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

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

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

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

  M_ϵ is the U-spin breaking "spurion"

  - M_ϵ 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): $t_0[\bar{f}_1],\; p_0[\bar{f}_0]\;;\quad s_1[\bar{f}_0]\epsilon,\; t_1[\bar{f}_1],\; p_1[\bar{f}_1]$

- The SCS decay amplitudes to $O(\epsilon)$, for f_1, f_0 final states ($U_3 = 0$),

$$\sqrt{2}A(\bar{D}^0 \to f_0) = (\lambda_s - \lambda_d)\, s_1[f_0]\,\epsilon - \lambda_b\, 2\, p_0[f_0] + O(\epsilon^2)$$
$$\sqrt{2}A(\bar{D}^0 \to f_1) = (\lambda_s - \lambda_d)\, t_0[f_1] - \lambda_b\, p_1[f_1]\,\epsilon + O(\epsilon^2)$$

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

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

$$A_{\rm CF}(\bar{D}^0 \to f_1) = V_{cs}V_{ud}^*(t_0[f_1] - \frac{1}{2}\; t_1[f_1]\,\epsilon + O(\epsilon^2))$$
$$A_{\rm DCS}(\bar{D}^0 \to f_1) = V_{cd}V_{us}^*(t_0[f_1] + \frac{1}{2}\; t_1[f_1]\,\epsilon + O(\epsilon^2))$$

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

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

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

- Expressed as exclusive sums over all decays, obtain

$$\frac{\Gamma_3}{\Gamma} = -\frac{\sum_{f_{\rm CP}} \Gamma_3(f_{\rm CP}) + \sum_{f,\bar{f}} \Gamma_3(f,\bar{f})}{\sum_{f_{1,{\rm CP}}} |t_0[f_1]|^2 + \sum_{f_1,\bar{f}_1} (|t_0[f_1]|^2 + |t_0[\bar{f}_1]|^2) + O(\epsilon)}$$

where

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

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

  - 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, knowledge of how large $|\Gamma_3|/\Gamma$ can reasonably be improves

- for the branching ratios

$$\left|\frac{A(D^0\to\pi^+\pi^-)}{A(D^0\to K^+K^-)}\right| = (1.82\pm 0.02)^{-1} \sim 1 + 2\mathrm{Re}\left(\frac{s_1\epsilon}{t_0}\right) + O(\epsilon^2)$$

and similarly for (Grossman, Robinson '12)

$$\left|\frac{A(D^0\to\pi^+\rho^-)}{A(D^0\to K^+K^{*-})}\right| = 1.59\pm 0.10, \quad \left|\frac{A(D^0\to\pi^-\rho^+)}{A(D^0\to K^-K^{*+})}\right| = 1.33\pm 0.05$$

- above suggests that $s_1\epsilon/t_0 \sim 0.25 - 1$ in PP, and is smaller in VP than PP, but precise statements are difficult due to unknown strong phases

- for SCS PP direct CP asymmetries

$$A_{\rm CP}^{\rm dir}(D^0 \to \pi^+\pi^-, K^+K^-) \leq O(\text{few} \times 0.1\%) \sim \pm 2 \left|\frac{\lambda_b}{\lambda_s}\right| {\rm Im}\left(\frac{p_0}{t_0}\right) \sin\gamma + O(\epsilon).$$

- for SCS VP direct CP asymmetries, have an HFAG bound

$$A_{\rm CP}(D^0 \to \pi^+\pi^-\pi^0) < -0.0023 \pm 0.0042$$

and a new LHCb result

  - $\Delta A_{\rm CP} \Rightarrow p_0 \lesssim t_0$ in PP modes

Examples of CPVINT

- SCS decays to CP eigenstates, e.g. $D^0 \to K^+K^-\,,\ \pi^+\pi^-$

$$\Gamma(D^0(t) \to f) \propto \exp[-\hat{\Gamma}_{D^0\to f}\ t], \qquad \Gamma(\overline{D^0}(t) \to f) \propto \exp[-\hat{\Gamma}_{\overline{D^0}\to f}\ t]$$

Time-dependent CP asymmetry: $A_\Gamma \equiv (\hat{\Gamma}_{D^0\to f} - \hat{\Gamma}_{\overline{D^0}\to f})/2\Gamma \neq 0$

$$A_\Gamma \text{ from CPVINT } \propto \sin\phi_{\lambda_f}\,, \qquad A_\Gamma \text{ from CPVMIX} \propto |q/p| - |p/q|$$

- DCS decays to non-CP eigenstates, e.g. wrong sign $D^0 \to K^+\pi^-$ vs $\bar{D}^0 \to K^-\pi^+$

$$\Gamma(D^0(t) \to K^+\pi^-) \propto e^{-\Gamma_D t}(a^+ + b^+ t + c^+ t^2), \quad \Gamma(\bar{D}^0(t) \to K^-\pi^+) \propto e^{-\Gamma_D t}(a^- + b^- t + c^- t^2)$$

Time-dependent CP asymmetries: $b^+ - b^- \neq 0, \quad c^+ - c^- \neq 0$

$$\phi_{\lambda_f} + \phi_{\lambda_{\bar{f}}} \neq 0 \ \Rightarrow\ b^+ - b^- \neq 0 \text{ from CPVINT}$$

$$|q/p| - |p/q| \neq 0 \ \Rightarrow\ b^+ - b^- \neq 0 \text{ from CPVMIX}$$