Absorptive and Dispersive CP violation in $D^0 - \overline{D}^0$ mixing

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Plan

- Introduction
- Formalism for absorptive and dispersive CPV in $D^0 - \overline{D}^0$ mixing
- Indirect CPV phenomenology
- U-spin and Approximate Universality
  - How large is indirect CPV in the SM?
- How large is the current window for New Physics (NP)?
- Prospects for measuring SM indirect CPV

Introduction

- In the SM, CP violation (CPV) in $D^0 - \overline{D}^0$ mixing and D decays enters at $O(V_{cb}V_{ub}/V_{cs}V_{us}) \sim 10^{-3}$, due to weak phase γ, yielding all 3 types of CPV:
  - direct CPV (dCPV)
  - CPV in pure mixing (CPVMIX): due to interference between dispersive and absorptive mixing amps
  - CPV in the interference of decays with and without mixing (CPVINT)
- Primary interest is in CPVMIX and CPVINT, both of which result from mixing, and which we refer to as “indirect CPV"
  - upper bounds suggest dCPV is already in the SM QCD “brown muck"

- We are interested in the following questions:
  - How large are the indirect CP asymmetries in the SM?
  - What is the appropriate minimal parametrization of indirect CPV?
  - How large is the current window for new physics (NP)?
  - Can this window be closed at HL-LHCb and Belle-II?
- To answer, we develop the description of CPVINT in terms of generally final state dependent dispersive and absorptive CPV phases ϕ_f^M and ϕ_f^Γ for CP conjugate final states f, $\bar{f}$. - introduced by Branco, Lavoura, Silva ('99)
- ϕ_f^M and ϕ_f^Γ parametrize CPVINT contributions from interference of D^0 decays with and without dispersive mixing, and with and without absorptive mixing
  - These are separately measurable CPV effects

- NP is most likely to appear in dispersive short distance mixing amplitudes
- SM dispersive and absorptive mixing amplitudes are due to long distance off-shell and on-shell intermediate states.
  - subleading $O(V_{cb}V_{ub}/V_{cs}V_{us})$ decay amplitudes $\propto e^{i\gamma}$ yield indirect CPV
- can not currently be calculated from first principles QCD
- meaningful SM estimates of ϕ_f^M, ϕ_f^Γ can be made using $SU(3)_F$ flavor symmetry arguments, yielding
  - a minimal parametrization of indirect CPV: approximate universality
  - estimates of the SM indirect CP asymmetries

Formalism

- time-evolution of linear combination $a|D^0\rangle + b|\overline{D}^0\rangle$ follows from Schrodinger equation,

$$i\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = H\begin{pmatrix} a \\ b \end{pmatrix} \equiv (M - \tfrac{i}{2}\,\Gamma)\begin{pmatrix} a \\ b \end{pmatrix} .$$

  - transition amplitudes

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

  - M_{12} is the dispersive mixing amplitude
    Γ_{12} is the absorptive mixing amplitude

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

  - mass and width differences expressed in terms of x, y

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

- introduce three "theoretical" physical mixing parameters

$$x_{12} \equiv 2|M_{12}|/\Gamma_D, \quad y_{12} \equiv |\Gamma_{12}|/\Gamma_D, \quad \phi_{12} \equiv \arg(M_{12}/\Gamma_{12})$$

  - ϕ_{12} is the CPV phase responsible for CPVMIX
  - CP conserving observables: $|x| = x_{12} + O(\mathrm{CPV}^2),\ |y| = y_{12} + O(\mathrm{CPV}^2)$

- Time-evolved meson solutions, for $t \lesssim \tau_D$: $\quad (D^0(0) = D^0,\ \overline{D}^0(0) = \overline{D}^0)$
  e.g. mixed components

$$\langle \overline{D}^0 | D^0(t) \rangle = e^{-i\left(M_D - i\frac{\Gamma_D}{2}\right)t} \left(e^{-i\delta_M} M_{12}^* - \tfrac{1}{2}\Gamma_{12}^*\right) t, \ldots$$

  - $\delta_M = \pi/2$ is a CP-even "dispersive strong phase", originating from the time derivative. Contributes to strong phase differences in indirect CPV

The dispersive and absorptive CPV phases ϕ_f^M, ϕ_f^Γ

- CPVINT observables for CP-conjugate final states $f = \bar{f}$:

$$\lambda_f^M \equiv \frac{M_{12}}{|M_{12}|}\frac{A_f}{\overline{A}_f} = \eta_f^{CP}\left|\frac{A_f}{\overline{A}_f}\right| e^{i\,\phi_f^M}\,, \quad \lambda_f^\Gamma \equiv \frac{\Gamma_{12}}{|\Gamma_{12}|}\frac{A_f}{\overline{A}_f} = \eta_f^{CP}\left|\frac{A_f}{\overline{A}_f}\right| e^{i\,\phi_f^\Gamma}\,.$$

with the decay amplitudes $A_f = \langle f|\mathcal{H}|D^0\rangle\,, \quad \bar{A}_f = \langle f|\mathcal{H}|\bar{D}^0\rangle$

- pairs of CPVINT observables for non-CP conjugate final states $f \neq \bar{f}$:

$$\lambda_f^M \equiv \frac{M_{12}}{|M_{12}|}\frac{A_f}{\overline{A}_f} = \left|\frac{A_f}{\overline{A}_f}\right| e^{i(\phi_f^M - \Delta_f)}\,, \quad \lambda_f^\Gamma \equiv \frac{\Gamma_{12}}{|\Gamma_{12}|}\frac{A_f}{\overline{A}_f} = \left|\frac{A_f}{\overline{A}_f}\right| e^{i(\phi_f^\Gamma - \Delta_f)}\,,$$

$$\lambda_{\bar{f}}^M \equiv \frac{M_{12}}{|M_{12}|}\frac{A_{\bar{f}}}{\overline{A}_{\bar{f}}} = \left|\frac{A_{\bar{f}}}{\overline{A}_{\bar{f}}}\right| e^{i(\phi_f^M + \Delta_f)} \quad \lambda_{\bar{f}}^\Gamma \equiv \frac{\Gamma_{12}}{|\Gamma_{12}|}\frac{A_{\bar{f}}}{\overline{A}_{\bar{f}}} = \left|\frac{A_{\bar{f}}}{\overline{A}_{\bar{f}}}\right| e^{i(\phi_f^\Gamma + \Delta_f)}\,.$$

  - Δ_f is the strong phase difference between $\overline{A}_f$ and A_f, and between $A_{\bar{f}}$ and $\overline{A}_{\bar{f}}$

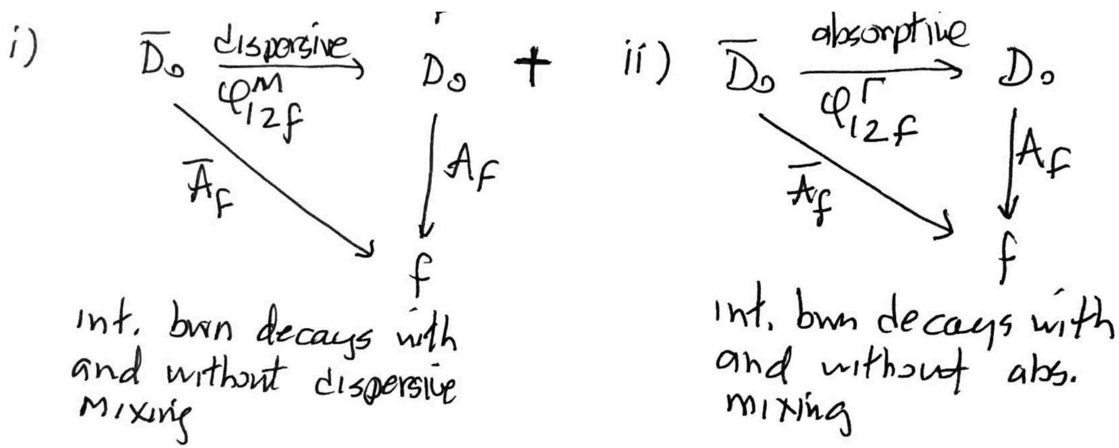
- relation to the CPVMIX phase: $\phi_{12} = \arg(M_{12}/\Gamma_{12}) = \phi_M^f - \phi_\Gamma^f$

- Hadronic $D^0(t)$ and $\overline{D}^0(t)$ decay amplitudes sum over contributions with and without mixing,

$$A(D^0(t) \to f) = \langle \overline{D}^0 | D^0(t) \rangle \bar{A}_f + \langle D^0 | D^0(t) \rangle A_f ,$$
$$A(\overline{D}^0(t) \to f) = \langle D^0 | \overline{D}^0(t) \rangle A_f + \langle \overline{D}^0 | \overline{D}^0(t) \rangle \bar{A}_f \, .$$

  - Time-dependent decay rates given in terms of CPVINT observables $\lambda^M_{f,\bar{f}}$, $\lambda^\Gamma_{f,\bar{f}}$

- ϕ^M_{12} and ϕ^Γ_{12} are the CPV phase differences between mixed and unmixed decay amps
- The strong phase differences are sum of $\delta^M = \pi/2$ and $\pm\Delta_f$ (dispersive mixing), $\pm\Delta_f$ (absorptive mixing)



- In SM Cabibbo favored/ doubly Cabibbo suppressed decays (CF/DCS) the CPVINT phases are universal, e.g. $D^0 \to K\pi,\ K^*\pi$,...

$$\phi^M_{\rm cfds} \equiv \phi^M_f\,, \qquad \phi^\Gamma_{\rm cfds} \equiv \phi^\Gamma_f\,, \quad f \in {\rm CF/DCS}$$

  - also true under the well motivated assumption that CF/DCS decays do not contain NP weak phases,
    - NP with non-negligible direct CPV in DCS/CF decays, which evades ϵ_K bounds, must be very exotic or tuned Bergmann, Nir

- In SM singly Cabibbo suppressed decays (SCS), e.g. $D^0 \to \pi^+\pi^-,\ K^+K^-$,... the CPVINT phases have small final state dependence due to the subleading QCD penguin decay amplitudes.

- The more familiar general CPV observables

$$\text{CPVMIX}: \quad \left|\frac{q}{p}\right| - 1$$

$$\text{CPVINT}: \; \phi_{\lambda_f} = \arg\left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right), \quad \text{for } f = \bar{f}$$

- Relation to absorptive and dispersive CPVINT phases ($\phi_{12} = \phi_f^M - \phi_f^\Gamma$)

$$\left|\frac{q}{p}\right| - 1 = \frac{x_{12}\, y_{12} \sin\phi_{12}}{x_{12}^2 + y_{12}^2}\; [1 + O(\sin\phi_{12})]$$

$$\tan 2\phi_{\lambda_f} = -\left(\frac{x_{12}^2 \sin 2\phi_f^M + y_{12}^2 \sin 2\phi_f^\Gamma}{x_{12}^2 \cos 2\phi_f^M + y_{12}^2 \cos 2\phi_f^\Gamma}\right).$$

  - same number of CPV quantities in each description

Indirect CPV phenomenology

- CPV requires non-trivial CPV “weak phase" differences (ϕ_w) and CP conserving “strong phase" differences (δ_s) between interfering amplitudes

$\Rightarrow$ CP asymmetries $\propto \sin\delta_{\rm s}\, \sin\phi_{\rm w}$

  - this dependence is manifest in the absorptive/dispersive CPV phase formalism

Examples:

- The CPVMIX “wrong sign" semileptonic CP asymmetry

$$
\begin{aligned}
a_{\rm SL} &\equiv \frac{\Gamma(D^0(t)\to \ell^- X) - \Gamma(\overline{D^0}(t)\to \ell^+ X)}{\Gamma(D^0(t)\to \ell^- X) + \Gamma(\overline{D^0}(t)\to \ell^+ X)}\,, \\
&= \frac{2x_{12}\, y_{12}\, \sin\delta^M\, \sin\phi_{12}}{x_{12}^2 + y_{12}^2 - 2\cos\phi_{12}\cos\delta^M} \\
&= \frac{2x_{12}\, y_{12}}{x_{12}^2 + y_{12}^2}\, \sin\phi_{12}\,.
\end{aligned}
$$

  - note the importance of the dispersive “strong phase" $\delta^M = \pi/2$

- time-dependent CP asymmetries in SCS decays to CP conjugate final states ($f = \bar{f}$), e.g. $D^0 \to K^+K^-, \;\; \pi^+\pi^-$

- to good approximation, the decay widths take the exponential forms

$$\Gamma(D^0(t) \to f) = |A_f|^2 \exp[-\hat{\Gamma}_{D^0\to f}\, \tau], \quad \Gamma(\overline{D^0}(t) \to f) = |\bar{A}_f|^2 \exp[-\hat{\Gamma}_{\overline{D^0}\to f}\, \tau]$$

$$\begin{aligned} \text{CP asymmetry :} \quad \Delta Y_f &\equiv \frac{\hat{\Gamma}_{\overline{D}^0\to f} - \hat{\Gamma}_{D^0\to f}}{2} \\ &= \eta^f_{CP}\,(-x_{12}\sin\phi^M_f\,\sin\delta^M + a^d_f\, y_{12}\cos\phi^\Gamma_f) \\ &= \eta^f_{CP}\,(-x_{12}\sin\phi^M_f + a^d_f\, y_{12})\,, \end{aligned}$$

  - ΔY_f depends on ϕ^M_f, but not ϕ^Γ_f:
    - for $f = \bar{f}$, no strong phase difference between A_f, $\overline{A}_f$.
      Thus, the only available CP-even strong phase is $\delta^M = \pi/2$
      $\Rightarrow$ asymmetry purely dispersive in origin!

  - up to subleading dCPV contribution (second term), where

$$a^d_f = 1 - \left|\bar{A}_f/A_f\right| = -2r_f\sin\delta_f\;\sin\phi_f\,.$$

- CF/DCS decays for $f \neq \bar{f}$, e.g. $D^0 \to K^\pm \pi^\mp$: the wrong sign $D^0(t) \to f$ and $\overline{D}^0 \to f$ decay widths expressed as

$$\Gamma(D^0(t) \to \bar{f}) = e^{-\tau} |A_f|^2 \left(R_f^+ + \sqrt{R_f^+} c_f^+ \, \tau + c_f'^+ \, \tau^2 \right) ,$$

$$\Gamma(\overline{D}^0(t) \to f) = e^{-\tau} |\bar{A}_{\bar{f}}|^2 \left(R_f^- + \sqrt{R_f^-} c_f^- \, \tau + c_f'^- \, \tau^2 \right) ,$$

and $R_f^\pm$ are the DCS to CF ratios $R_f^+ = |A_{\bar{f}}/A_f|^2, \quad R_f^- = |\bar{A}_f/\bar{A}_{\bar{f}}|^2$

- linear time dependence yields the CPVINT asymmetry (assuming no NP weak phases in CF/DCS)

$$\Delta c_f = x_{12} \sin \phi^M_{\text{cfds}} \cos \Delta_f - y_{12} \sin \phi^\Gamma_{\text{cfds}} \sin \Delta_f$$

  - the $\cos \Delta_f$ and $\sin \Delta_f$ dependence originates from the strong phase differences $\Delta_f - \delta^M$ (dispersive), and Δ_f (absorptive)

U-spin decomposition and Approximate Universality

- using CKM unitarity ($\lambda_i = V_{ci}\, V_{ui}^*$)

$$\Gamma_{12} = -\sum_{i,j=d,s} \lambda_i \lambda_j \Gamma_{ij} = \frac{(\lambda_s - \lambda_d)^2}{4}\,\Gamma_5 + \frac{(\lambda_s - \lambda_d)\lambda_b}{2}\,\Gamma_3 + \frac{\lambda_b^2}{4}\,\Gamma_1$$

$$M_{12} = -\sum_{i,j=d,s} \lambda_i \lambda_j \Gamma_{ij} = \frac{(\lambda_s - \lambda_d)^2}{4}\,M_5 + \frac{(\lambda_s - \lambda_d)\lambda_b}{2}\,M_3 + \frac{\lambda_b^2}{4}\,M_1$$

- the $\Gamma_i,\ \ M_i$ are $\Delta U_3 = 0$ elements of U-spin multiplets. They enter at different orders in ϵ, which characterizes $SU(3)_F$ breaking. Nominally, $\epsilon = O(0.2)$.

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

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

- Γ_5, M_5 dominate and yield ΔM, $\Delta\Gamma$, or $y_{12},\ x_{12}$
- $\delta\Gamma_{12} \propto \Gamma_3, \quad \delta M_{12} \propto M_3 \ \Rightarrow$ CPV via $\gamma = \arg(\lambda_b)$
- neglect $O(\lambda_b^2)$ effects of Γ_1, M_1

- define a pair of theoretical CPV phases ϕ_5^M, ϕ_5^Γ, with respect to the dominant ($\Delta U = 2$) direction in the complex mixing plane $\propto (\lambda_s - \lambda_d)^2$,

$$\phi_5^\Gamma \equiv \arg\left(\frac{\Gamma_{12}}{\Gamma_{12}^{\Delta U=2}}\right) \approx \mathrm{Im}\left(\frac{2\lambda_b}{\lambda_s - \lambda_d}\frac{\Gamma_3}{\Gamma_5}\right) \sim \left|\frac{\lambda_b}{\theta_c}\right| \sin\gamma \times \frac{1}{\epsilon}$$

and similarly for ϕ_5^M

- for “nominal” U-spin breaking,

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

- another useful theoretical phase, defined with respect to the $\Delta U = 2$ direction:

$$\phi_5 \equiv \arg\left(\frac{q}{p}\frac{1}{\Gamma_{12}^{\Delta U=2}}\right)$$

- How large is the final state dependence in ϕ_f^M, ϕ_f^Γ, and ϕ_{λ_f} compared with our theoretical phases?
  - Define misalignment between the general phases and the “theoretical" phases

$$\delta\phi_f \equiv \phi_f^\Gamma - \phi_5^\Gamma = \phi_f^M - \phi_5^M = \phi - \phi_{\lambda_f}$$

- CF/DCS decays with no NP weak phases: misalignment is known and negligible, i.e. $\delta\phi_f = O(\lambda_b^2/\theta_c^2)$

$$\Rightarrow \quad \phi_f^\Gamma = \phi_5^\Gamma, \quad \phi_f^M = \phi_5^M, \quad \phi_{\lambda_f} = \phi_5, \quad f \in \mathrm{cf/dcs}$$

- $\delta\phi_f$ is related to direct CPV: $\delta\phi_f = A_{CP}^{\mathrm{dir}}(D \to f)\cot\delta$, where δ is the strong phase difference in A_{CP}^{dir}
  - $D^0 \to K^+K^-, \pi^+\pi^-$: $\quad A_{CP}^{\mathrm{dir}} \lesssim O(10^{-3}) \;\Rightarrow\; \delta\phi_f \lesssim O(10^{-3})$

    $\Rightarrow$ small misalignment compared to expected BelleII/LHCb sensitivity

- U-spin argument: in the SM, $\phi_5^\Gamma = O(1/\epsilon)$, due to $O(\epsilon^2)$ cancelation in $\Gamma_5 \approx \Gamma_{12}$, but for SCS decays, $\delta\phi_f = O(1)$ in U-spin breaking,

$$\Rightarrow \quad \frac{\delta\phi_f}{\phi_5^\Gamma} = O(\epsilon) \text{ in SCS } \mathrm{D}^0 \text{ decays}$$

  yielding parametric suppression of misalignment relative to ϕ_5^Γ

- We conclude that in the SM, relative to the theoretical phases ϕ_5^M, ϕ_5^Γ, and ϕ_5, the final state dependence in ϕ_f^M, ϕ_f^Γ, and ϕ_{λ_f}, respectively, is
  - subleading in $SU(3)_F$ and negligible compared to the expected LHC-b/Belle-2 sensitivity, in SCS decays
  - entirely negligible in CF/DCS decays

- Thus, a single pair of dispersive and absorptive phases suffices to parametrize all indirect CPV effects, which we can identify with our theoretical phases ϕ_5^Γ, ϕ_5^M. (The more familiar CPVINT phases ϕ_{λ_f} can be replaced with the single phase ϕ_5, combined with $1 - |q/p|$)

  -we refer to this fortunate circumstance as approximate universality

Approximate universality generalizes beyond the SM under the following conservative assumptions about subleading decay amplitudes containing new weak phases:

- they can be neglected in CF/DCS decays

- in SCS decays their magnitudes are similar to, or smaller than the SM QCD penguin amplitudes, as already hinted at by the experimental bounds on $A_{CP}^{\rm dir}(K+K?, +?)$

- These assumptions can ultimately be tested by future direct CPV measurements

How large is the current window for NP?

- we have estimated that $\phi_5^M \sim \phi_5^\Gamma \sim 3 \times 10^{-3}$ for nominal U-spin breaking, $\epsilon \sim 0.2$.

$$\Rightarrow \quad \phi_{12} = \phi_5^M - \phi_5^\Gamma \sim 3 \times 10^{-3}$$

- a more sophisticated U-spin breaking analysis of ϕ_5^Γ, which can be improved with more data on D^0 decays, yields a similar result, $\phi_5^\Gamma \lesssim 0.005$

- the tightest upper bounds on ϕ_{12} are obtained in the "superweak limit" (Ciuchini et al '07; Grossman, Perez, Nir '09; A.K., Sokoloff '09):

  - neglect subleading decay weak phases in indirect CPV

    $\Rightarrow$ $\phi_{12} \neq 0$ would be purely dispersive, entirely due to short-distance NP in M_{12} (short distance NP is negligible)

$$\phi_{12} = \phi_5^M, \quad \phi_5^\Gamma = 0, \quad (\phi_{\lambda_f} \to \phi_5)$$

    $\Rightarrow$ only one CPV phase ϕ_{12} controls all indirect CPV. Therefore superweak fits to CPV data are highly constrained (${1 - |q/p|}$ and ϕ_5 are related)

- HFAG, UTFIT superweak fits to ϕ_{12}:

$$\text{HFAG}: \phi_{12} = 0.00 \pm 0.03\ (1\sigma), \quad [-0.07, +0.08]\ (95\%\text{c.l.})$$
$$\text{UTfit}: \phi_{12} = 0.01 \pm 0.05\ (1\sigma), \quad [-0.10, +0.15]\ (95\%\text{c.l.})$$

  - comparing with U-spin based estimate of ϕ_{12}, current CPV measurements

    $\Rightarrow$ $O(10)$ window for NP

- HFAG superweak fit for ϕ and $|q/p|$ at 1σ,

$$\phi = 0.00 \pm 0.01\ [\text{rad}], \quad |q/p| = 1.002 \pm 0.014\,.$$

  - in superweak limit

$$\tan 2\phi_5 = -\frac{x_{12}^2}{x_{12}^2 + y_{12}^2}\ \sin 2\phi_5^M$$

$$\tan \phi_5 \approx \left(1 - \left|\frac{q}{p}\right|\right)\ \frac{x}{y}$$

Prospects for measuring SM indirect CPV

- fit mixing data to ϕ_5^Γ and ϕ_5^M
  - in practice, equivalent to "traditional" two parameter fit: for ϕ_5, $|q/p|$
  - less constrained than superweak: current HFAG errors increase by $O(10)$ compared to superweak fit.
  - LHCb/Belle-II improved sensitivity will help overcome this
- useful to consider the approximate universality relation

$$\tan 2(\phi + \phi_5^\Gamma) \approx -\frac{x_{12}^2}{x_{12}^2 + y_{12}^2} \sin 2\phi_{12}$$

  - our rough U-spin based estimate $\phi_5^\Gamma \sim 0.003$ and the current ≈ 0.01 HFAG 1σ error on ϕ are not far apart. Going forward, the LHS $\Rightarrow$ already must move beyond superweak to two - parameter fits apologies for not checking updated projections

- projected Belle-II errors at 50 ab^{-1} on $x\,(\%)$, $y\,(\%)$, $|q/p|\,(\%)$, and $\phi\,(\mathrm{mrad})$ from $D^0 \to K_s\pi^+\pi^-$ alone, and on $\Delta Y_f\ (\%)$ from $D^0 \to K^+K^-, \pi^+\pi^-$ (Belle2-NOTE-PH-2015-002):

$$0.11(x), 0.05(y), 7.2(|q/p|), 72(\phi), 0.04(\Delta Y_f)$$

- old projections for LHCb upgrade, based on $50\ \mathrm{fb}^{-1}$ for $q/p|$ from $a_{\rm sl}(D^0 \to K\mu\nu)$; x, y, ϕ from $D^0 \to K_s\pi^+\pi^-$, and ΔY_f from $D^0 \to K^+K^-, \pi^+\pi^-$ (1208.3355)

$$0.015\,(x),\ 0.010\,(y),\ 1.0\,(|q/p|),\ 52\,(\phi),\ 0.004\,(\Delta Y_f)\,.$$

- illustration of the potential reach in ϕ_{12}^M and ϕ_{12}^Γ: the above LHCb errors, using the error correlation matrix of the present Belle-II measurements, and the central values $x = 0.35\%$, $y = 0.58\%$, yields the 95% CL errors

$$\delta\phi_{12}^M = \pm 34 \, [\mathrm{mrad}] \, , \quad \delta\phi_{12}^\Gamma = \pm 17 \, [\mathrm{mrad}] \, .$$

  - Naively halving the errors, for HE-LHCb with 300 fb^{-1} approaches the SM level, but perhaps factor of 2 too large

- ideas for using a binned model independent Dalitz Plot analysis at LHCb, e.g. in $D^0 \to K_s \pi^+ \pi^-$ could further reduce the errors (1209.0172, C. Thomas, G. Wilkinson)

- an HFAG type fit to all possible measurements will also help

- However, an LHCb at the HE-LHC would be most welcome!