Describing Charm time dependent CPV in the Precision Era

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based on A.K. and Luca Silvestrini, 2001.07207, in PRD

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Plan

- Introduction
- Absorptive and dispersive CPV in $D^0 - \overline{D}^0$ mixing
- Time-dependent CPV phenomenology
- Intrinsic mixing phases and approximate universality
  - SCS decays
  - CF/DCS decays $D^0 \to K^{\pm} X$
  - CF/DCS decays $D^0 \to K^0 X\,, \overline{K}^0 X$
- Current Status
- Conclusion

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)
- Our interest here is in CPVMIX and CPVINT, both of which result from mixing, and which we refer to as “indirect CPV"

- 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 in the Belle-II / LHCb Precision Era ?

- Answers:
  - obtained by describing CPVINT in terms of pairs of dispersive and absorptive CPV phases ϕ_f^M and ϕ_f^Γ, for CP conjugate final states f, $\bar{f}$
  - they parametrize CPVINT from interference of D^0 decays with and without dispersive mixing, and with and without absorptive mixing.
  - These are separately measurable effects.
  - simpler, physically transparent expressions for indirect CP asymmetries
  - can be used to extract an “intrinsic" pair of pure mixing absorptive and dispersive phases ${\phi_2}^M$, ${\phi_2}^\Gamma$, with controlled errors

    $\Rightarrow$ these two phases suffice to describe indirect CPV in the precision charm era
  - SM estimates for ${\phi_2}^M$, ${\phi_2}^\Gamma$ follow from U-spin arguments

Absorptive and Dispersive CPV

- Transition amplitudes for $D^0 - \overline{D}^0$ mixing:

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

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

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

- Mass eigenstates $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$:
  - mass and width differences expressed in terms of parameters 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

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

  - ϕ_{12} is the CPV phase responsible for CPVMIX, e.g. semileptonic CP asymmetry

$$A_{\rm SL} = \frac{2x_{12}\, y_{12}}{x_{12}^2 + y_{12}^2}\, \sin\phi_{12}\,.$$

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

- Time-evolved meson solutions, for $t \lesssim \tau_D$:

  For $D^0(0) = D^0$, the mixed component at time t,

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

  - the phase $\pi/2$ is a CP-even “dispersive strong phase”
  - it is the CP-even phase difference between the interfering dispersive and absorptive mixing amplitudes required to obtain CPVMIX
  - It contributes to the CP-even “strong phase” differences required for CPVINT

The dispersive and absorptive CPV phases ϕ_f^M, ϕ_f^Γ in hadronic decays

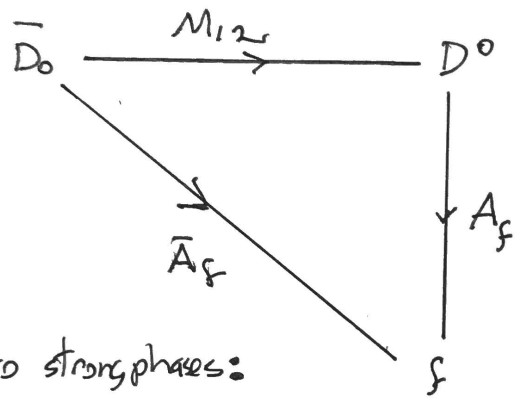
- Hadronic $D^0(t)$, $\overline{D}^0(t)$ decay amplitudes sum over contributions with/without mixing:

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

$A_f \equiv \langle f | \mathcal{H} | D^0 \rangle \, , \quad \bar{A}_f \equiv \langle f | \mathcal{H} | \bar{D}^0 \rangle$ are the decay ampltiudes

- ϕ_f^M and ϕ_f^Γ are the CPV phase differences between the two interfering amplitudes:

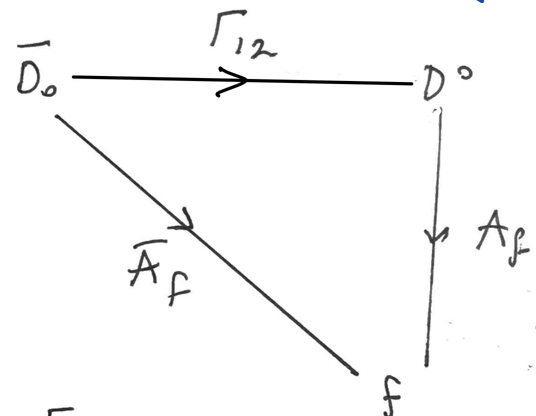
1) Interference between decays with and without dispersive mixing:



up to strong phases:

$$\phi_f^M = \arg\left(\frac{M_{12}}{|M_{12}|} \frac{A_f}{\bar{A}_f}\right)$$

2) Interference between decays with and without absorptive mixing



$$\phi_f^\Gamma = \arg\left(\frac{\Gamma_{12}}{|\Gamma_{12}|} \frac{A_f}{\bar{A}_f}\right)$$

Relation to "phenomenological" CPVINT parameters

- The more familiar "phenomenological" CPV observables are

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

$$\text{CPVINT}: \ \phi_{\lambda_f} = \arg\left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right)$$

- Relation to absorptive and dispersive CPVINT phases

$$\left|\frac{q}{p}\right| - 1 = \frac{x_{12}\, y_{12} \sin\phi_{12}}{x_{12}^2 + y_{12}^2} + O(\text{CPV}^3), \qquad \text{where} \quad \phi_{12} = \phi_f^M - \phi_f^\Gamma$$

$$\sin 2\phi_{\lambda_f} = -\left(\frac{x_{12}^2 \sin 2\phi_f^M + y_{12}^2 \sin 2\phi_f^\Gamma}{x_{12}^2 + y_{12}^2}\right) + O(\text{CPV}^3)$$

  - ϕ_{λ_f} is a sum over ϕ_f^M and ϕ_f^Γ, weighted by the dispersive and absorptive contributions to the CP averaged mixing probability, $x_{12}^2/(x_{12}^2 + y_{12}^2)$ and $y_{12}^2/(x_{12}^2 + y_{12}^2)$

- Note $\phi_{12} = \phi_f^M - \phi_f^\Gamma$ $\Rightarrow$ same number of CPV quantities in each description
- The LHCb parametrization $\Delta x,\ \Delta y$ (introduced in the $D^0 \to K_S\pi^+\pi^-$ analyses):

$$2\,\Delta x_f = x\cos\phi_{\lambda_f}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) + y\sin\phi_{\lambda_f}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right),$$
$$2\,\Delta y_f = y\cos\phi_{\lambda_f}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) - x\sin\phi_{\lambda_f}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right).$$

In terms of the dispersive and absorptive phases:

$$\Delta x_f = -y_{12}\sin\phi_f^\Gamma, \qquad \Delta y_f = x_{12}\sin\phi_f^M$$

$\Rightarrow$ Δx_f and Δy_f are equivalent to the absorptive and dispersive CPVINT phases, up to the corresponding mixing factors

Time dependent CPV phenomenology

I. Phenomenology of SCS decays to CP eigenstates

The phases ϕ_f^M, ϕ_f^Γ enter the decay widths via the dimensionless observables λ_f^M, λ_f^Γ:

- for SCS decays to CP-eigenstate final states, e.g. $f = K^+K^-$, $\pi^+\pi^-$:

  $\bar{f} = \eta_f^{CP}\, f$, where $\eta_f^{CP} = +(-)$ for f a CP-even (odd) final state

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

  - recall CP asymmetries require both a CPV phase difference (ϕ), and a CP-even phase difference (δ), between interfering amplitudes $\Rightarrow$ $A_{CP} \propto \sin\phi\sin\delta$

  - Trivial strong phase difference between A_f, $\overline{A}_f$ $\Rightarrow$ the only CP-even phase available for generation of CP asymmetries is the dispersive phase $\pi/2$

  - Therefore, for CP-eigenstate final states, in general, CPVINT is purely dispersive and $\propto x_{12}\sin\phi_f^M$

- time-dependent decay widths for SCS decays to CP eigenstates ($\tau \equiv \Gamma_D t$), e.g. $f = K^+K^-,\ \pi^+\pi^-,\ \rho^0\pi^0,\ K^{*+}K^{*-},\ \rho^+\rho^-$

$$\Gamma(\overset{(-)}{D^0}(t) \to f) = e^{-\tau}|\overset{(-)}{A}_f|^2 \left(1 + c_f^{\pm}\, \tau + c_f'^{\pm}\, \tau^2\right)$$

Ignores $\mathcal{O}(\tau^2)$

- The time-dependent CPVINT asymmetry:

$$\Delta Y_f \equiv \frac{(c_f^+ - c_f^-)}{2} = \frac{\hat{\Gamma}_{\overline{D}^0 \to f} - \hat{\Gamma}_{D^0 \to f}}{2}$$

  - CPVINT is indeed purely dispersive (up to dCPV effects):

$$\Delta Y_f = \eta_{CP}^f \left(-x_{12} \sin\phi_f^M + a_f^d\, y_{12}\right)$$

  - In usual parametrization:

$$\Delta Y_f = \frac{y}{2} \cos\phi_{\lambda_f} \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) - \frac{x}{2} \sin\phi_{\lambda_f} \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) + a_f^d\, |y|$$

    - physical interpretation is obscured by combination of CPVMIX and CPVINT contributions

II. Phenomenology of CF/DCS Decays to $K^{\pm}X$

- For CF/DCS decays to $K^{\pm}X$, e.g. $K^+\pi^-$, $K^+\pi^-\pi^0$ (and SCS decays to non-CP eigenstates), have two pairs of observables: one for f, one for $\bar{f}$ ADD second eq:

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

.

  - Δ_f = strong phase difference between $\overline{A}_f$ (DCS) and A_f (CF), and between $A_{\bar{f}}$ (DCS) and $\overline{A}_{\bar{f}}$ (CF)

  - the total CP-even phase difference between decays with and without mixing is $\Delta_f - \pi/2$ (dispersive) and Δ_f (absorptive)

    $\Rightarrow$ time dependent CPVINT asymmetries

$$\propto x_{12}\,\sin\phi_f^M\,\cos\Delta_f \quad \text{(dispersive mixing)}$$

$$\propto y_{12}\,\sin\phi_f^\Gamma\,\sin\Delta_f \quad \text{(absorptive mixing)}$$

- The time-dependent decay widths for the "wrong sign" decays $D^0 \to \bar{f}$ and $\overline{D}^0 \to f$, e.g. $\bar{f} = K^+\pi^-$, are:

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

where $R_f^+ = |A_{\bar{f}}/A_f|^2$, $R_f^- = |\bar{A}_f/\bar{A}_{\bar{f}}|^2$

- In the SM, and in NP models with negligible dCPV in CF/DCS decays, obtain the wrong sign CP asymmetry at linear order in τ:

$$\delta c_{\mathrm{WS},f} \equiv \tfrac{1}{2}(c_{\mathrm{WS},f}^+ - c_{\mathrm{WS},f}^-) = x_{12}\sin\phi_f^M \cos\Delta_f - y_{12}\sin\phi_f^\Gamma \sin\Delta_f$$

  - expected Δ_f dependence for dispersive and absorptive CPV
  - non-CP eigenstate final states (non-trivial Δ_f) yield sensitivity to ϕ_f^Γ

Intrinsic Mixing Phases and Approximate Universality

- To arrive at a minimal parametrization of indirect CPV effects in the precision era, we need to understand the final state dependence of ϕ_f^M , ϕ_f^Γ

- accomplished via a U-spin flavor symmetry decomposition of the SM mixing amplitudes. Using CKM unitarity:

$$\Gamma_{12}^{\mathrm{SM}} = \frac{(\lambda_s - \lambda_d)^2}{4}\,\Gamma_2 + \frac{(\lambda_s - \lambda_d)\lambda_b}{2}\,\Gamma_1 + \frac{\lambda_b^2}{4}\,\Gamma_0$$

  - $\Gamma_{2,1,0}$ are the $\Delta U_3 = 0$ elements of ΔU= 2, 1, 0 multiplets. Can be seen from their flavor structures

$$\Gamma_2 = \Gamma_{ss} + \Gamma_{dd} - 2\Gamma_{sd} \;\sim\; (\bar{s}s - \bar{d}d)^2 = O(\epsilon^2)\,,$$
$$\Gamma_1 = \Gamma_{ss} - \Gamma_{dd} \;\sim\; (\bar{s}s - \bar{d}d)(\bar{s}s + \bar{d}d) = O(\epsilon)\,,$$
$$\Gamma_0 = \Gamma_{ss} + \Gamma_{dd} + 2\Gamma_{sd} \;\sim\; (\bar{s}s + \bar{d}d)^2 = O(1)\,.$$

  - the orders in the U-spin breaking parameter ϵ are shown

  - M_{12}^{SM} is analogous (except for small internal b quark contributions in M_1, M_0)

- small $|\lambda_b/\lambda_s| \sim 0.7 \times 10^{-3}$ $\Rightarrow$ mass and width differences (x_{12} , y_{12}) are due to M_2 and Γ_2, even though $O(\epsilon^2)$
  - Therefore, U-spin breaking is large, e.g. large phase space effects Falk et al.
- CPV in mixing arises at $O(\epsilon)$, due to Γ_1 and M_1 ($\lambda_b \propto e^{i\,\gamma}$)
- Introduce the “intrinsic" pure mixing phases

$$\phi_2^\Gamma \equiv \arg\left[\frac{\Gamma_{12}}{\frac{1}{4}(\lambda_s - \lambda_d)^2\,\Gamma_2}\right], \quad \phi_2^M \equiv \arg\left[\frac{M_{12}}{\frac{1}{4}(\lambda_s - \lambda_d)^2\,M_2}\right],$$

$$\phi_2 \equiv \arg\left[\frac{q}{p}\,\frac{(\lambda_s - \lambda_d)^2}{4}\,\Gamma_2\right]$$

  - ϕ_2^Γ, ϕ_2^M, ϕ_2 are the intrinsic analogs of ϕ_f^M, ϕ_f^Γ, ϕ_{λ_f}, respectively
  - defined w.r.t the direction of the dominant $\Delta U = 2$ mixing amplitudes
  - in principle, can be measured on the lattice

- rough SM estimates of ϕ_2^Γ and, similarly, ϕ_2^M:

$$\phi_2^\Gamma \approx \mathrm{Im}\left(\frac{2\lambda_b}{\lambda_s - \lambda_d}\frac{\Gamma_1}{\Gamma_2}\right) \sim \left|\frac{\lambda_b}{\theta_c}\right| \sin\gamma \times \frac{1}{\epsilon},$$

  - CKM fits yield

$$\phi_2^\Gamma \sim \phi_2^M \sim (2.2 \times 10^{-3}) \times \left[\frac{0.3}{\epsilon}\right]$$

- a robust SM upper bound on $|\phi_2^\Gamma|$, via the relation $|\Gamma_2| \cong |y|\Gamma_D/\lambda_s^2$:

$$|\phi_2^\Gamma| = \left|\frac{\lambda_b\,\lambda_s\,\sin\gamma}{y}\right| \frac{|\Gamma_1|}{\Gamma_D} < 0.005\left(\frac{0.66\%}{|y|}\right)\epsilon_1[1 + O(\epsilon)]$$

where $\epsilon_1 \equiv |\Gamma_{dd} - \Gamma_{ss}|/|\Gamma_{sd}| = O(\epsilon)$. It is conservatively < 1.

  - used the upper bound (details in A.K., L. Silvestrini, to appear)

$$\Gamma_{sd}/\Gamma_D < 1 + O(\epsilon)$$

  - The $O(\epsilon)$ correction is expected to be small - it does not depend on U-spin breaking from phase space effects - those enter at $O(\epsilon^2)$

Approximate Universality in the SM

- the misalignments $\delta\phi_f$ between the measured phases ϕ_f^M, ϕ_f^Γ, ϕ_{λ_f}, and their intrinsic counterparts are equal in magnitude,

$$\delta\phi_f = \phi_f^\Gamma - \phi_2^\Gamma = \phi_f^M - \phi_2^M = \phi_2 - \phi_{\lambda_f},$$

  - in general, up to strong phases, $\delta\phi_f = \arg\left[\frac{A_f}{\overline{A}_f}(\lambda_s - \lambda_d)^2\right]$

- what are the misalignments in the various classes of decays? or, what is the uncontrolled theoretical error on measurements of ϕ_2^M, ϕ_2^Γ?

- CF/DCS decays to $K^\pm X$, e.g. $K^+\pi^-$, $K^+\pi^-\pi^0$:

$$\delta\phi_f = \arg\left[-\frac{V_{cs}^* V_{ud}}{V_{cd} V_{us}^*}(\lambda_s - \lambda_d)^2\right] = O\left(\frac{\lambda_b^2}{\lambda_s^2}\right) \sim 4\times 10^{-5}$$

  - the misalignment is negligible, i.e. $\delta\phi_f \sim 10^{-2}\,\phi_2^{M,\Gamma}$

- SCS decays, e.g. K^+K^-, $\pi^+\pi^-$: for CP eigenstate final states

$$\delta\phi_f = -2r_f \cos\delta_f \sin\gamma = -a_f^d \cot\delta_f \sim a_f^d$$

  - In the SM, $r_f = |P/T|$ is the relative magnitude of the subleading QCD penguin amplitude, while $\phi_f = -\gamma$ and δ_f are the weak and strong phase differences
  - formally, $\delta\phi_f/\phi_2^{M,\Gamma} = O(\epsilon)$, but U-spin $\Rightarrow$ $\delta\phi_{K^+K^-} \sim -\delta\phi_{\pi^+\pi^-}$, or

$$\frac{1}{2}(\phi^{M,\Gamma}_{K^+K^-} + \phi^{M,\Gamma}_{\pi^+\pi^-}) = \phi_2^{M,\Gamma}[1 + O(\epsilon^2)]$$

  - ϵ could be large, but $O(\epsilon^2)$ suppression of QCD penguin pollution in the average is welcome, if the K^+K^- and $\pi^+\pi^-$ modes are included in global fits to ϕ_2^M, ϕ_2^Γ .

CPVINT in $D^0 \to K_S\pi^+\pi^-$

- Two-step transitions $D^0 \to [K_{S,L} \to \pi^+\pi^-] + X$. The CP conjugate final states $f = [\pi^+\pi^-]X$, $\bar{f} = \overline{[\pi^+\pi^-]X}$ related by interchanging Dalitz plot variables

- Including kaon CPV, the misalignment satisfies $(\epsilon_K \cong (1.62 + i\,1.53) \times 10^{-3})$

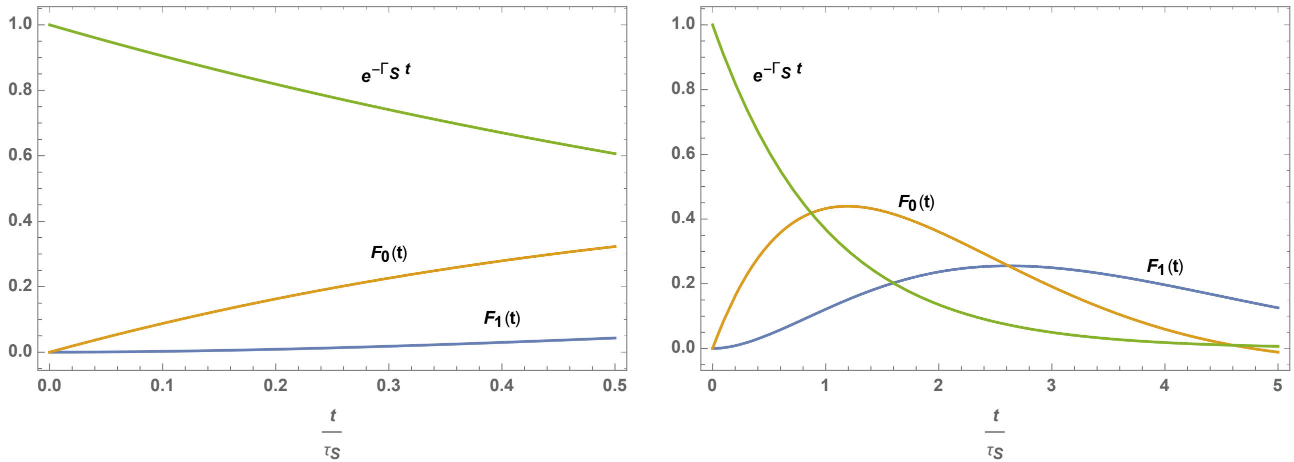
$$\delta\phi_f = 2\,\epsilon_I + \left|\frac{\lambda_b}{\lambda_s}\right| \sin\gamma = 3.7 \times 10^{-3},$$

  - $O(0.1\ \phi_2^{M,\Gamma})$ corrections, due to the DCS amplitudes and ϵ'/ϵ, can be neglected

- Incorporating ϵ_K effects in the $K_S\pi^+\pi^-$ time dependent CP asymmetries, obtain for example (t' is the time at which $K_{S,L}$ decay following their production)

$$\Gamma_f - \overline{\Gamma}_{\bar{f}} \propto e^{-\tau} \Big\{ \epsilon_R\, F_0(t') + \sqrt{R_f}\,\tau \Big[(x_{12}\cos\Delta_f + y_{12}\sin\Delta_f)\,\epsilon_I\, F_1(t') + \Big(\underbrace{x_{12}\sin\Big(\phi_2^M + \left|\frac{\lambda_b}{\lambda_s}\right|\sin\gamma\Big)}_{\Delta y_f}\cos\Delta_f + \underbrace{y_{12}\sin\Big(\phi_2^\Gamma + \left|\frac{\lambda_b}{\lambda_s}\right|\sin\gamma\Big)}_{\Delta x_f}\sin\Delta_f\Big)\, e^{-\Gamma_S t'} \Big] \Big\},$$

  - The F_0 term is associated with dCPV   Grossman, Nir 2012
  - The F_1 term includes the $K_S - K_L$ interference effects



Shown are $F_0(t)$, $F_1(t)$, and $\exp[-\Gamma_S t]$, plotted over a short time interval of relevance to LHCb (left), and a longer time interval of relevance to Belle-II (right)

- over the time scale for observed K^0's at LHCb, e.g. $t' \lesssim 0.5\tau_S$, cancelations suppress F_1 to the few percent level, while $e^{-\Gamma_S t'} = O(1)$
  - ϵ_K effects in the CPVINT asymmetries can be neglected at LHCb
- over the Belle-II time scale, e.g. $t' \lesssim 10\tau_S$, the cancelation in F_1 subsides, and ϵ_K ultimately dominates the SM CPVINT asymmetries.

- Approximate universality generalizes beyond the SM under conservative assumptions regarding subleading decay amplitudes containing new weak (CPV) phases:
  - they can be neglected in CF/DCS decays: exotic flavor structure would be required to evade ϵ_K constraint
  - in SCS decays, they are of similar magnitude to, or smaller than SM QCD penguins, as hinted at by ΔA_{CP}
  - these assumptions can ultimately be tested via dCPV measurements
- Significant short distance NP in ϕ_2^M would be consistent with approximate universality

Current Status

- Superweak Approximation: in the past, sensitivity to ϕ_{12} of $O(100)$ mrad probed short-distance NP
  - it was appropriate to neglect the effects of weak phases in subleading decay amplitudes in indirect CPV observables. In this limit,

$$\phi_f^M = \phi_2^M = \phi_{12}, \quad \phi_f^\Gamma = 0\,, \quad \phi_{\lambda_f} = \phi_2$$

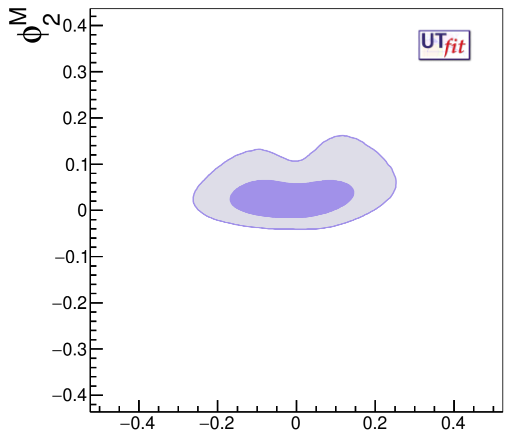
  - the superweak global fit is highly constrained, since there is only one CPV phase controlling all indirect CPV phenomena

    fit for ϕ_2^M, x_{12}, y_{12}

  - Prior to the new LHCb ΔY_f measurements (for experimental inputs mostly from HFLAV), we obtained $\phi_2^M = (-0.5 \pm 2.2)\,\%$ at 1σ
  - similar to the HFLAV result, $\phi_2^M = (-0.4 \pm 1.6)\,\%$
  - comparison with the SM estimate, $\phi_2^M = O(0.2\%)$, implies an order of magnitude window for NP

Approximate Universality global fit

- the approximate universality global fit is less constrained, given there are now two CPVINT phases, ϕ_2^M and ϕ_2^Γ. Includes new LHCb ΔY_f measurements:



ϕ_2^Γ vs. ϕ_2^M at 68% CL, 95% CL

- fit for ϕ_2^M, ϕ_2^Γ, x_{12}, y_{12}
- equivalent to traditional fit for $|q/p|$, ϕ_2, x, y

$$\phi_2^M = (2.5 \pm 2.8)\,\%, \qquad \phi_2^\Gamma = (-1.2 \pm 10.2)\% \quad \text{at } 1\sigma$$

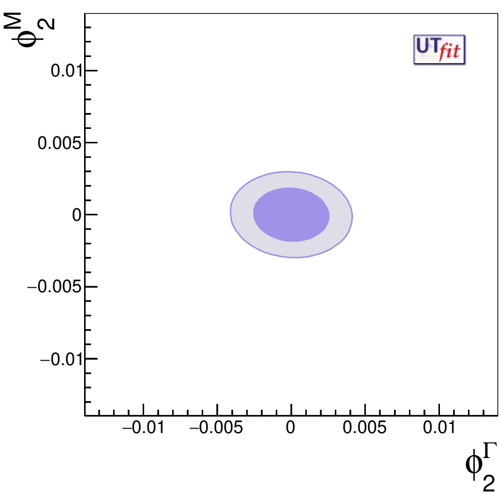
- error on ϕ_2^M is approximately a factor of 3-4 smaller than on ϕ_2^Γ, and not much larger than superweak
- largely due to ΔY_f, which only depends on ϕ_2^M

Future projections

Naively estimated experimental uncertainties for the LHCb Phase II Upgrade era, for three CF/DCS decay modes: $D^0 \to K_S\pi^+\pi^-,\ K^+\pi^-, K^+\pi^-\pi^+\pi^-$

$\delta(x_{\rm CP})$ $3.8 \cdot 10^{-5}$	$\delta(y_{\rm CP})$ $8.6 \cdot 10^{-5}$	$\delta(\Delta x)$ $1.7 \cdot 10^{-5}$	$\delta(\Delta y)$ $3.8 \cdot 10^{-5}$	1903.03074, scaled by luminosity
$\delta(y'_+)_{K\pi}$ $3.2 \cdot 10^{-5}$	$\delta(y'_-)_{K\pi}$ $3.2 \cdot 10^{-5}$	$\delta(x'_+)^2_{K\pi}$ $1.7 \cdot 10^{-6}$	$\delta(x'_-)^2_{K\pi}$ $1.7 \cdot 10^{-6}$	1712.03220, scaled by luminosity
$\delta(x_{K\pi\pi\pi})$ $2 \cdot 10^{-5}$	$\delta(y_{K\pi\pi\pi})$ $2 \cdot 10^{-5}$	$\delta(\lvert q/p\rvert_{K\pi\pi\pi})$ $2 \cdot 10^{-3}$	$\delta(\phi_{K\pi\pi\pi})$ $0.1°$	1812.07638 (Yellow Rept)

$300\,{\rm fb}^{-1}$



$\delta\phi_2^M \approx \pm 0.12°$ at 1σ

$\delta\phi_2^\Gamma \approx \pm 0.17°$ at 1σ

- suggests SM sensitivity may be achievable

Conclusion

- Description of indirect CPV in terms of the absorptive and dispersive phases ϕ_f^M, ϕ_f^Γ is simpler, and more physically transparent than ϕ_{λ_f}, $|q/p| - 1$

- ultimately, the goal is to measure the two intrinsic mixing phases ϕ_2^M, ϕ_2^Γ

- approximate universality: minimal uncontrolled pollution from the decay amplitudes

  - CF/DCS decays: to excellent approximation, it is negligible in the CF/DCS decays in the SM, and in models with negligible new weak phases in these decays

  - SCS decays: there is uncontrolled final state dependent pollution, formally of $O(\epsilon)$ for individual modes, but of $O(\epsilon^2)$ for the sum $\phi_{K^+K^-}^{M,\Gamma} + \phi_{\pi^+\pi^-}^{M,\Gamma}$

  - in the future, it will be instructive to compare the SCS and CF/DCS measurements

- ϕ_2^M and ϕ_2^Γ can, in principle, be measured on the lattice - this will be crucial for a precision test of the SM

- There is currently an $O(10)$ window for NP in mixing CPV. Based on very naive projections, SM sensitivity may be achieved during the LHCb Phase II era, particularly if ϕ_2^M, ϕ_2^Γ lie on the high end of the U-spin based estimates