Describing Charm time dependent CPV in the Precision Era

Alex Kagan

University of Cincinnati

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

Thanks to Yuval Grossman, Zoltan Ligeti, Gilad Perez, Alexey Petrov for collaboration in earlier stages

FPCP 2021

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

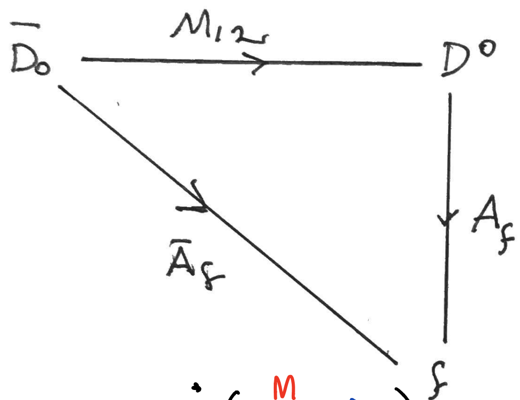
- Hadronic $D^0(t)$, $\overline{D}^0(t)$ decay amplitudes sum over contributions with/without mixing:

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

$A_f \equiv \langle f | \mathcal{H} | D^0 \rangle$, $\bar{A}_f \equiv \langle f | \mathcal{H} | \bar{D}^0 \rangle$ are the decay amplitudes, strong phase diff. Δ_f

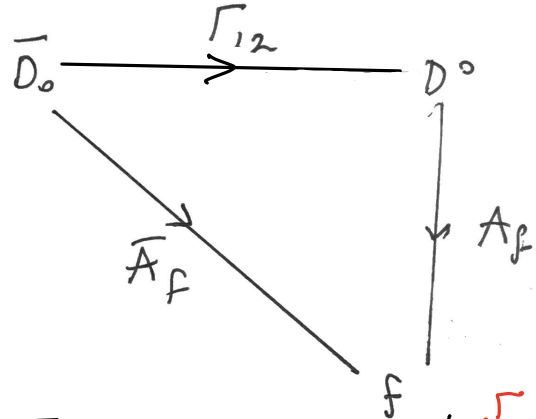
- ϕ_f^M and ϕ_f^Γ are the CPV phase differences between the two interfering amplitudes:

1) Interference between decays with and without dispersive mixing:



$$\lambda_f^M \equiv \frac{M_{12}}{|M_{12}|} \frac{A_f}{\bar{A}_f} \propto e^{i(\varphi_f^M - \Delta_f)}$$

2) Interference between decays with and without absorptive mixing



$$\lambda_f^\Gamma \equiv \frac{\Gamma_{12}}{|\Gamma_{12}|} \frac{A_f}{\bar{A}_f} \propto e^{i(\varphi_f^\Gamma - \Delta_f)}$$

Relation to "phenomenological" CPVINT parameters

- The more familiar "phenomenological" CPV observables are

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

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

- 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

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

- CP eigenstate final states: Trivial strong phase difference between A_f, $\overline{A}_f$
  $\Rightarrow$ only CP-even phase available is the dispersive phase $\pi/2$

  - Therefore, CPVINT is purely dispersive and $\propto x_{12} \sin\phi_f^M$

- Non-CP eigenstate final states: non-trivial strong phase Δ_f between $\overline{A}_f$ and A_f, and between $A_{\bar{f}}$ and $\overline{A}_{\bar{f}}$

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

    $\Rightarrow$ time dependent CPVINT asymmetries

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

- only non-CP eigenstate final states (non-trivial Δ_f) are sensitive to ϕ_f^Γ

Phenomenology of SCS decays to CP eigenstates

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

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

- The time-dependent CPVINT asymmetry:

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

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

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

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

  - 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 $K^\pm X$

- 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:

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

  - $\Delta_f =$ strong phase difference between $\overline{A}_f$ (DCS) and A_f (CF)
  - obtain 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:

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

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

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

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

  - $M_{12}^{\rm SM}$ 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 (thanks to Y. Grossman):

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

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

- inclusive dispersion relation estimates are an order of magnitude smaller
  $\phi_2^M \approx -\phi_2^\Gamma \approx 2 \times 10^{-4}$ (Li et al. 2001.04079)

- 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, $\delta\phi_f = \arg\left[\frac{A_f}{\bar{A}_f}(\lambda_s - \lambda_d)^2\right]$

- 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 $D^0(t) \to [K_{S,L}(t') \to \pi^+\pi^-] + X$. 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

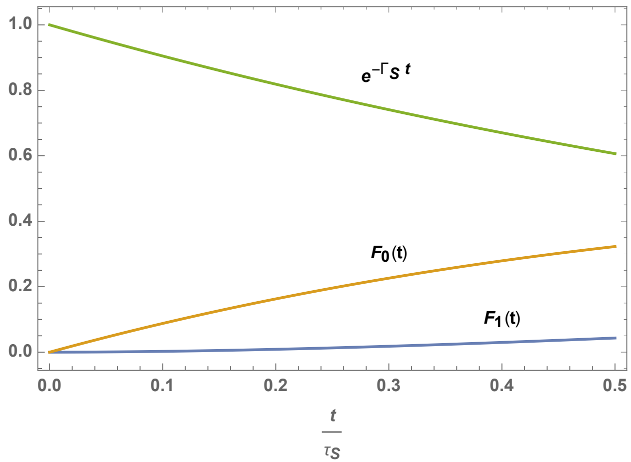
- Incorporating ϵ_K effects in the $K_S\pi^+\pi^-$ time dependent CP asymmetries, obtain for example (t' is the time at which $K_{S,L}$ decay following their production)

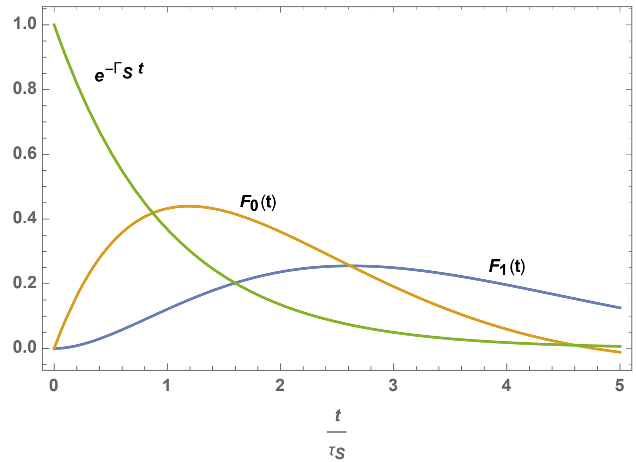
$$\Gamma_f - \overline{\Gamma}_{\bar{f}} \propto e^{-\tau} \Big\{ \epsilon_R\, F_0(t') + \sqrt{R_f}\,\tau \Big[(x_{12}\cos\Delta_f + y_{12}\sin\Delta_f)\,\epsilon_I\, F_1(t') + \Big(\underbrace{x_{12}\sin\Big(\phi_2^M + \left|\frac{\lambda_b}{\lambda_s}\right|\sin\gamma\Big)}_{\Delta y_f} \cos\Delta_f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

  - F_0 term: associated with dCPV Grossman, Nir 2012

  - F_1 term: ϵ_K effects from $K_S - K_L$ interference and $\phi_f^{M,\Gamma}$ - negligible at LHCb

Cancelations at LHCb time scale $t' \lesssim \frac{\tau_{K_S}}{2} \Rightarrow F_1(t') < 0.05$ at LHCb





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)

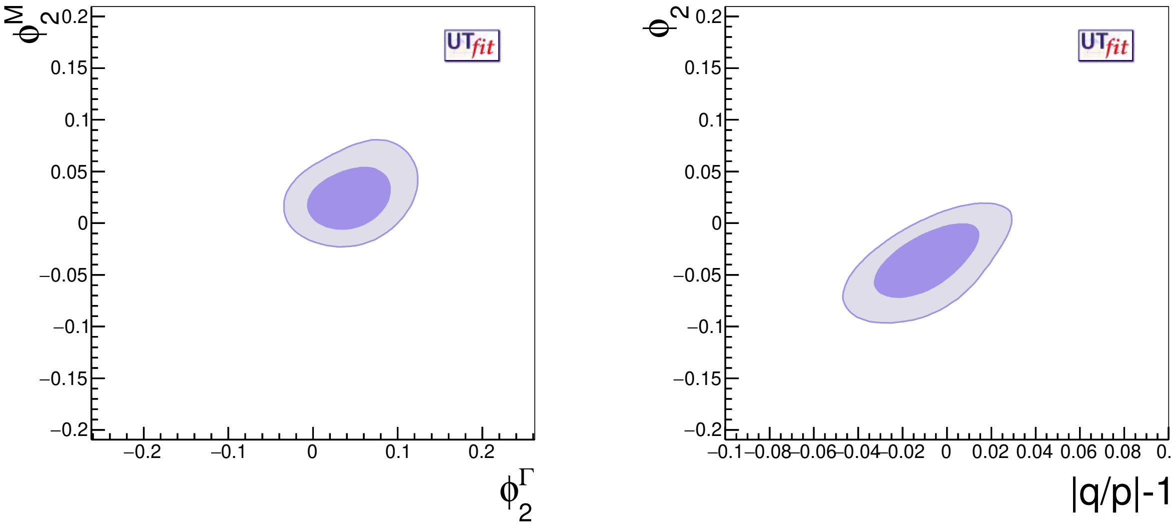
- over the time scale for observed K^0's at LHCb, e.g. $t' \lesssim 0.5\tau_S$, cancelations suppress F_1 to the few percent level, while $e^{-\Gamma_S t'} = O(1)$
  - ϵ_K effects in the CPVINT asymmetries can be neglected at LHCb
- over the Belle-II time scale, e.g. $t' \lesssim 10\tau_S$, the cancelation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

- Approximate universality fit for ϕ_2^M, ϕ_2^Γ, x_{12}, y_{12}: data mostly from HFLAV, and new LHCb t-dependent $K_s\pi\pi$ (2106.03744) and K^+K^-, $\pi^+\pi^-$ (2105.09889) analyses

68% CL and 95% CL



$$\phi_2^M = (2.3 \pm 2.0)\,\%, \quad \phi_2^\Gamma = (4.4 \pm 3.2)\%, \quad x_{12} = 0.4 \pm 0.05\,\%, \quad y_{12} = 0.56 \pm 0.05\%$$

- in the "phenomenological" CPV parametrization: $(\varphi_2, |q/p|, x, y)$

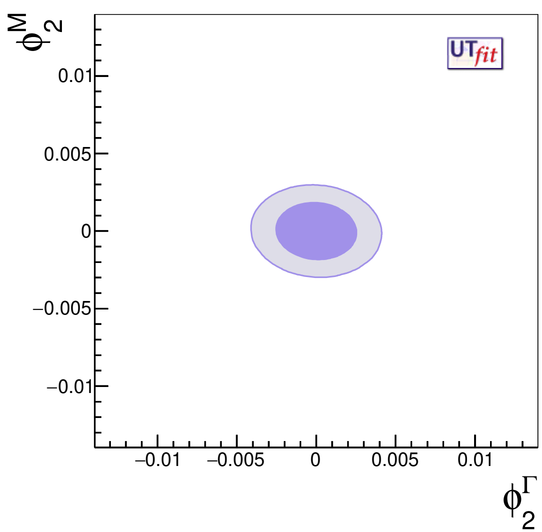
  $\phi_2 = (-3.7 \pm 2.4)\,\%, \quad |q/p| - 1 = (-0.9 \pm 1.5)\%$

- 1σ errors about an order of magnitude greater than expected SM ranges for ϕ_2^M, ϕ_2^Γ

Future projections

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

$\delta(x_{\rm CP})$ $3.8\cdot10^{-5}$	$\delta(y_{\rm CP})$ $8.6\cdot10^{-5}$	$\delta(\Delta x)$ $1.7\cdot10^{-5}$	$\delta(\Delta y)$ $3.8\cdot10^{-5}$	1903.03074, scaled by luminosity
$\delta(y'_+)_{K\pi}$ $3.2\cdot10^{-5}$	$\delta(y'_-)_{K\pi}$ $3.2\cdot10^{-5}$	$\delta(x'_+)^2_{K\pi}$ $1.7\cdot10^{-6}$	$\delta(x'_-)^2_{K\pi}$ $1.7\cdot10^{-6}$	1712.03220, scaled by luminosity
$\delta(x_{K\pi\pi\pi})$ $2\cdot10^{-5}$	$\delta(y_{K\pi\pi\pi})$ $2\cdot10^{-5}$	$\delta(\lvert q/p\rvert_{K\pi\pi\pi})$ $2\cdot10^{-3}$	$\delta(\phi_{K\pi\pi\pi})$ 0.1°	1812.07638 (Yellow Rept)



1σ:

$\delta\phi_2^M \approx \pm 0.12°$

$\delta\phi_2^\Gamma \approx \pm 0.17°$

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