D-$\bar{D}$ MIXING IN THE SM

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- Introduction
- Estimating CP violation in the SM:
  - The "real SM" approximation
  - Beyond the "real SM" approximation:
    - future experimental prospects
    - theoretical arguments
- Conclusions

Based on Grossman, Kagan, Ligeti, Perez, Petrov & L.S., in preparation; special thanks to A.K.!

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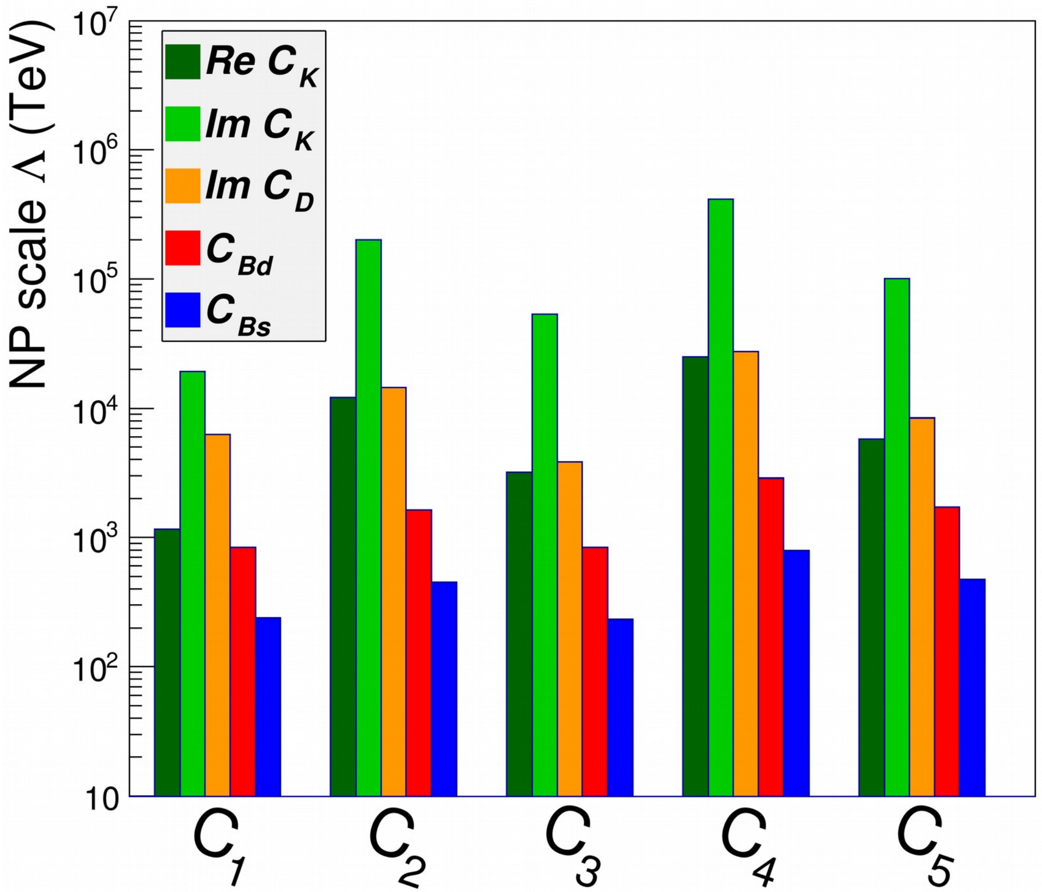
INTRODUCTION

- 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?



See talk by M. Bona on Thursday for update & details

D MIXING

- D mixing is described by:
  - Dispersive $D \to \bar{D}$ amplitude M_{12}
    - SM: long-distance dominated, not calculable
    - NP: short distance, calculable w. lattice
  - Absorptive $D \to \bar{D}$ amplitude Γ_{12}
    - SM: long-distance, not calculable
    - NP: negligible
  - Observables: $|M_{12}|$, $|\Gamma_{12}|$, $\Phi_{12}=\arg(\Gamma_{12}/M_{12})$

GIM ⇔ SU(3) (U-spin)

- Use CKM unitarity

  $V_{cd}V_{ud}^* + V_{cs}V_{us}^* + V_{cb}V_{ub}^* = \lambda_d + \lambda_s + \lambda_b = 0$

- eliminate λ_d and take λ_s real (all physical results convention independent)
- imaginary parts suppr. by $r = \mathrm{Im}\,\lambda_b/\lambda_s = 6.5\ 10^{-4}$
- M_{12}, Γ_{12} 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 $\Leftrightarrow$ SU(3) (U-spin)

- Write long-distance contributions to M_{12} and Γ_{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 $r/\varepsilon \sim 2\ 10^{-3} \sim 1/8°$ 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 Γ_{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}

"REAL SM" APPROXIMATION II

- Define $|D_{S,L}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$ 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 δ, with

$$\sqrt{2}\,\Delta m = \mathrm{sign}(\cos\Phi_{12})\sqrt{4|M_{12}|^2-|\Gamma_{12}|^2+\sqrt{(4|M_{12}|^2+|\Gamma_{12}|^2)^2-16|M_{12}|^2|\Gamma_{12}|^2\sin^2\Phi_{12}}}\,,$$

$$\sqrt{2}\,\Delta\Gamma = 2\sqrt{|\Gamma_{12}|^2-4|M_{12}|^2+\sqrt{(4|M_{12}|^2+|\Gamma_{12}|^2)^2-16|M_{12}|^2|\Gamma_{12}|^2\sin^2\Phi_{12}}}\,,$$

$$\delta = \frac{2|M_{12}||\Gamma_{12}|\sin\Phi_{12}}{(\Delta m)^2+|\Gamma_{12}|^2}\,, \qquad (7)$$

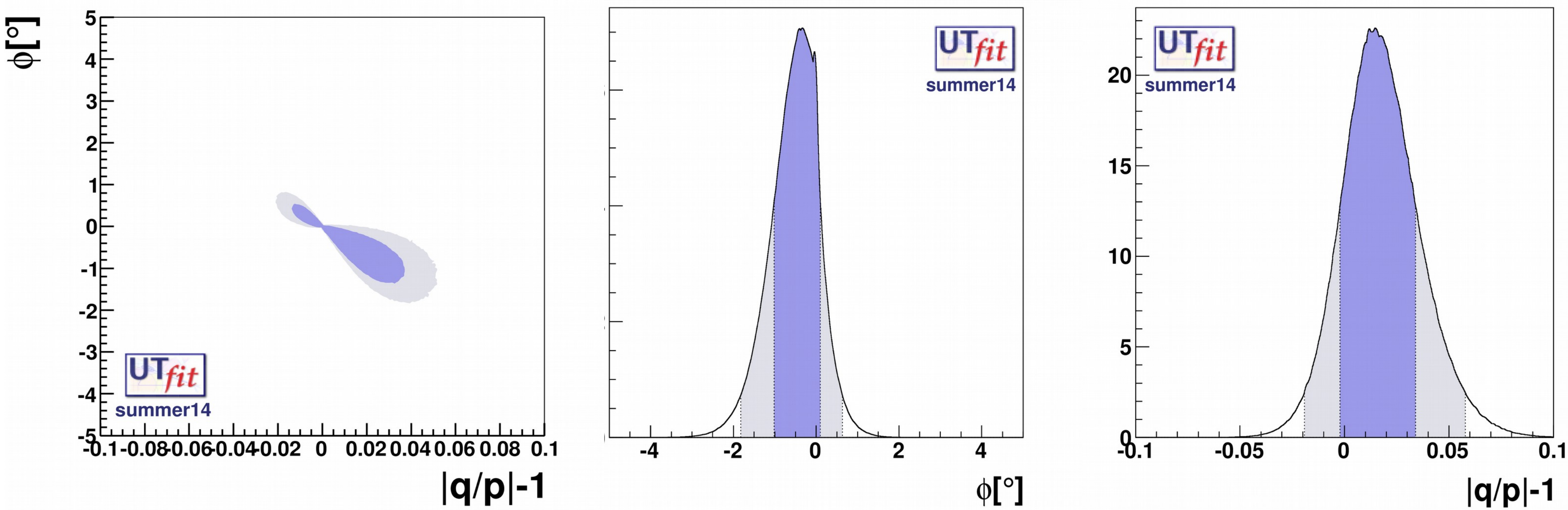
- Notice that $\phi=\arg(q/p)=\arg(y+i\delta x)$ - ~~$\arg\Gamma_{12}$~~
- $|q/p|\neq 1 \Leftrightarrow \phi\neq 0$ clear signals of NP

Ciuchini et al; Kagan & Sokoloff

CPV IN MIXING TODAY

- latest UTfit average (HFAG very similar):

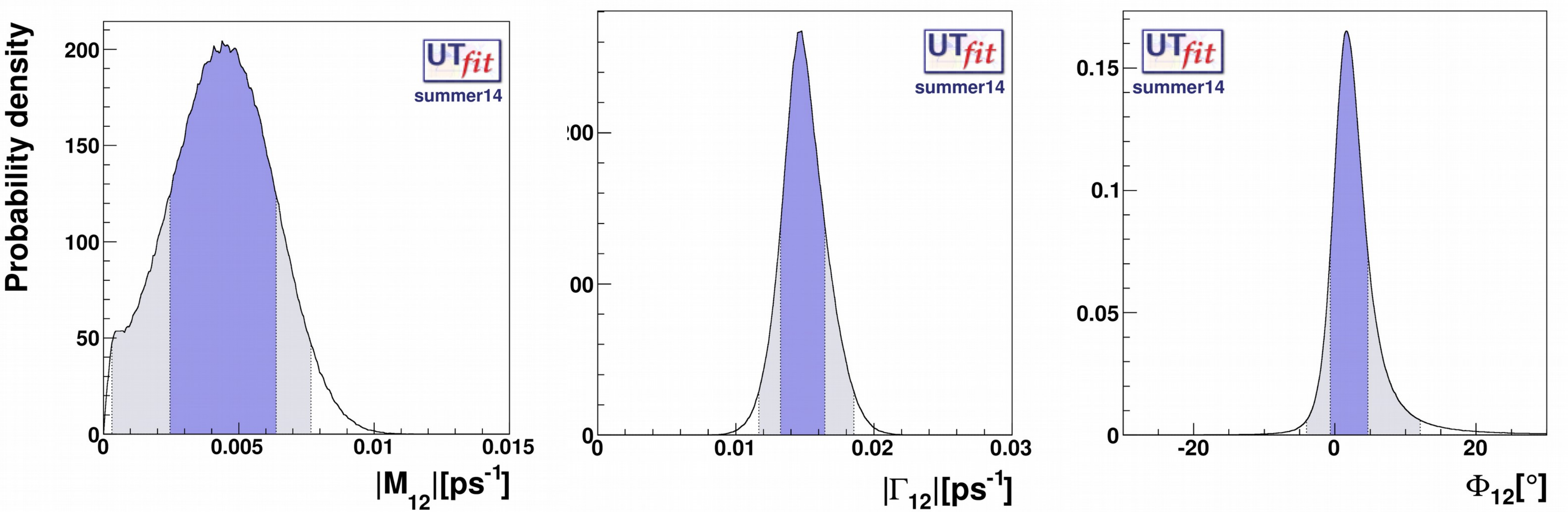
$x = (3.6 \pm 1.6)\ 10^{-3}$, $y = (6.1 \pm 0.6)\ 10^{-3}$,
$|q/p|-1 = (1.6 \pm 1.8)\ 10^{-2}$,
$\phi = \arg(q/p) = (0.45 \pm 0.56)°$



CPV IN MIXING TODAY II

- The corresponding results on fundamental parameters are

$|M_{12}| = (4 \pm 2)/\text{fs}$, $|\Gamma_{12}| = (15 \pm 2)/\text{fs}$ and $\Phi_{12} = (2 \pm 3)^\circ$



BEYOND THE "REAL SM"

- 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" II

- Relax the assumption of real Γ_{12}, introduce $\phi_{\Gamma 12} = \arg \Gamma_{12}$
- The relation between ϕ, x, y and δ is modified as follows:
  - $\phi = \arg(q/p) = \arg(y+i\delta x) - \phi_{\Gamma 12}$
- Can we extract $\phi_{\Gamma 12}$ from experimental data?
- How large can $\phi_{\Gamma 12}$ be in the SM?

BEYOND THE "REAL SM" III

- In principle, if decay amplitudes are not real, they affect the extraction of ϕ:

  $\phi \rightarrow \phi + \delta\phi_f$, 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, $\delta\phi_f = A_{CP}^{dir}(D \rightarrow f) \cot \delta_f$ (δ_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 ϕ_{12} and $\phi_{\Gamma 12}$ or, equivalently, for ϕ_{M12} and $\phi_{\Gamma 12}$

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

CHARM CPV @ HI-LUMI

- "Extreme" flavour experiment (LHCb upgrade L x 100)

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

- Naïve extrapolation, scaling LHCb upgrade estimates:
  - $\delta x = 1.5\ 10^{-5}$, $\delta y = 10^{-5}$, $\delta|q/p| = 10^{-3}$, $\delta\phi = .3°$ (from $K_s\pi\pi$); $\delta y_{CP} = \delta A_\Gamma = 4\ 10^{-6}$ (from K^+K^-)
  - $\delta\phi_{M12} = \pm\ 0.1°$ (1.7 mrad) and $\delta\phi_{\Gamma 12} = \pm\ 0.2°$ (3.4 mrad) @ 95% prob.
  - $\Lambda > 3\ 10^5$ TeV, close to the bound from ε_K

CAN WE ESTIMATE $\phi_{\Gamma 12}$ IN SM?

- $\Gamma_{12} = \Gamma_{12}^0 + \delta\Gamma_{12} = \lambda_s^2\,(\Delta U=2) + \lambda_s\lambda_b\,(\Delta U=2 + \Delta U=1) + O(\lambda_b^2) \sim \lambda_s^2\,\Gamma_5 + \lambda_s\lambda_b\,\Gamma_3$
- Γ_5 changes Uspin by two units, arises @ $O(\varepsilon^2)$
- Γ_3 changes Uspin by one unit, arises @ $O(\varepsilon)$
- Trade Γ_{12}^0 for $y\Gamma$, get $\phi_{\Gamma 12} \sim \mathrm{Im}\,\lambda_s\lambda_b/y\ \Gamma_3/\Gamma \sim 5\ 10^{-3}\,\Gamma_3/\Gamma$

ESTIMATING Γ_3/Γ

- Γ_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 Γ_3, using e.g. the general parameterization of U-spin amplitudes in SCS decays by Brod, Kagan, Grossman & Zupan

ESTIMATING Γ_3/Γ 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 $\phi_{\Gamma 12}$
- ϕ_{M12} might be estimated via dispersion rel.

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}, Γ_{12}, ϕ_{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 Γ_{12} are parametrically enhanced over CPV contributions to decay amplitudes
- Moreover, the latter are already constrained to lie below the future sensitivity in ϕ, and essentially vanish in the SM
- Generalizing the fit introducing $\phi_{\Gamma 12}$ captures dominant SM effects

CONCLUSIONS III

- Belle II/LHCb upgrade will probe ϕ_{M12} and $\phi_{\Gamma 12}$ at the level of 1°, while an "extreme" flavour experiment might reach the 0.1° level
- $\phi_{\Gamma 12}$ can be estimated using fits of SCS decay amplitudes (in particular PV ones)
- at present $\phi_{\Gamma 12}$ at the 0.3° level is plausible, but more data needed to refine this estimate; may also estimate ϕ_{M12} via disp. rel.

BACKUP SLIDES

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

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

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

Courtesy of A. Kagan

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

Courtesy of A. Kagan

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

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

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

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

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

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

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

Courtesy of A. Kagan

- 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, our knowledge of how large $|\Gamma_3|/\Gamma$ can reasonably be will improve

Courtesy of A. Kagan