CP violation in $D - \overline{D}$ mixing: Standard Model versus Current Bounds

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Introduction

CPV in charm provides a unique probe of New Physics (NP)

- sensitive to NP in the up sector
- SM charm physics is CP conserving to first approximation (2 generation dominance)

Nevertheless, the statement "any signal for CPV would be NP" needs sharpening due to continuing improvement in experimental bounds:

- In the SM, CPV in mixing enters at $O(V_{cb}V_{ub}/V_{cs}V_{us}) \sim 10^{-3}$
  - how large can SM indirect CPV really be?
- In the SM, direct CPV enters at $O([V_{cb}V_{ub}/V_{cs}V_{us}]\ \alpha_s/\pi) \sim 10^{-4}$ in singly Cabibbo suppressed decays (SCS)
  - how large can SM direct CPV really be?

A bit more detail on CPV in mixing (more later):

- transition amplitudes between the strong interaction meson eigenstates $\bar{D}^0$, D^0

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

- The mixing parameters [$\Gamma = (\Gamma_1 + \Gamma_2)/2$ = average decay width]

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

ϕ_{12} is a CP violating weak phase, responsible for CP violation in mixing

- Relations to CP conserving observables $|\Delta m|$, $|\Delta\Gamma|$:

$$|x| \equiv \frac{|\Delta m|}{\Gamma} = x_{12}\,[1 + O(\sin^2\,\phi_{12}\,)], \quad |y| \equiv \frac{|\Delta\Gamma|}{2\Gamma} = y_{12}\,[1 + O(\sin^2\,\phi_{12}\,)]$$

- relation to CP violation in pure mixing (CPVMIX): semileptonic CP asymmetry

$$a_{\rm SL} \equiv \frac{\Gamma(D^0(t) \to \ell^- X) - \Gamma(\overline{D^0}(t) \to \ell^+ X)}{\Gamma(D^0(t) \to \ell^- X) + \Gamma(\overline{D^0}(t) \to \ell^+ X)} = \frac{2\, x_{12}\, y_{12}\, \sin\phi_{12}}{x_{12}^2 + y_{12}^2}\, [1 + O(\sin\phi_{12})]$$

- CP violation in the interference of decays with and without mixing (CPVINT): time-dependent CP asymmetries

Example: SCS decays to CP eigenstates, $D^0 \to K^+K^-\,,\ \pi^+\pi^-$

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

The CP asymmetry: $\Delta Y_f \equiv (\hat\Gamma_{\overline{D^0}\to f} - \hat\Gamma_{D^0\to f})/2\Gamma_D$

$$\Delta Y_f = -x_{12} \sin\,\phi_{12}\, [1 + O(\sin\,\phi_{12})]$$
$$+ \text{ possible contributions from new weak phases in decay}$$

- to understand how large indirect CPV (CPVMIX & CPVINT) can be in the SM must improve on "$\sin\,\phi_{12}$ enters at $O(V_{cb}V_{ub}/V_{cs}V_{us})$"

Outline

- A model-independent upper bound on $\sin\phi_{12}$ in the SM - with Yuval Grossman and Zoltan Ligeti
  - the bound is proportional to an $SU(3)_F$ breaking parameter
  - this parameter can be bounded experimentally in the future
- Updated bounds on $\sin\,\phi_{12}$ from experiment - thanks to Rolf Andreasson, MIke Sokoloff for the fits
  - makes essential use of mode-independent relations between CPVMIX and CPVINT - Grossman, Nir, Perez; AK, Sokoloff
  - includes the recent CDF $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ time-integrated CP asymmetries

A model-independent bound on $\sin\,\phi_{12}$ in the SM

Three types of D decay

- Cabibbo Favored (CF)

$$c \to s\bar{d}u \quad (D \to K^-\pi^+)$$

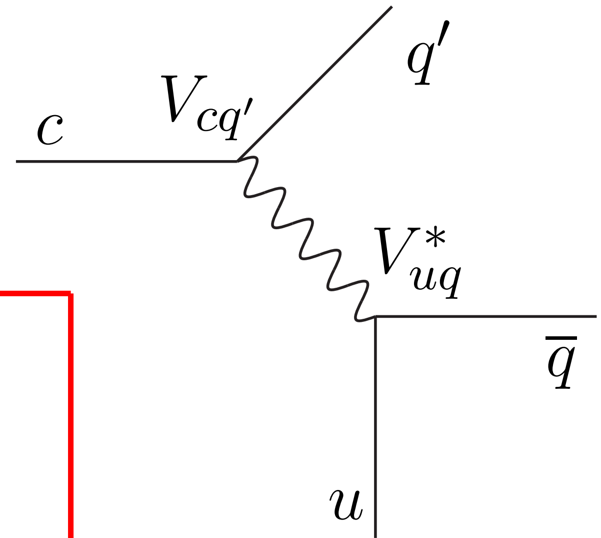
- Singly Cabibbo Suppressed (SCS)

$$c \to s\bar{s}u \quad (D \to K^-K^+)$$

$$c \to d\bar{d}u \quad (D \to \pi^-\pi^+)$$

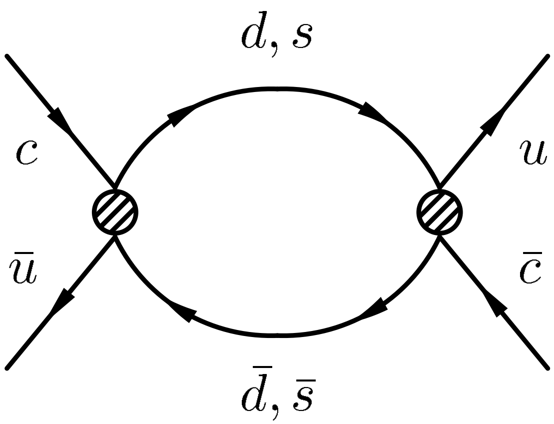
- Doubly Cabibbo Suppressed (DCS)

$$c \to d\bar{s}u \quad (D \to \pi^-K^+)$$



$$q, q' = s, d$$

$$\Gamma_{12} = -\left(\lambda_s^2\,\Gamma_{ss} + 2\lambda_s\lambda_d\,\Gamma_{sd} + \lambda_d^2\,\Gamma_{dd}\right), \quad \text{where} \quad \lambda_p = V_{cp}V_{up}^*$$



Γ_{xy} in the OPE picture

Γ_{ss} : via SCS operators $c \to s\bar{s}u$

Γ_{dd} : via SCS operators $c \to d\bar{d}u$

Γ_{sd} : via CF & DCS operators $c \to s\bar{d}u\,,\ c \to d\bar{s}u$

- from a sum over decays to common exclusive final states Falk et al.:

$$\lambda_s^2\Gamma_{ss} = \Gamma\sum_n \eta_{\rm CP}(n)\cos\delta_n\sqrt{\mathcal{B}(D^0\to n)\mathcal{B}(D^0\to\bar{n})}\,,\ \ldots.$$

δ_n = strong phase difference between $\mathcal{A}(D^0 \to n)$ and $\mathcal{A}(\bar{D}^0 \to n)$; $\eta_{\rm CP} = \pm 1$

Derivation of the SM bound

- using CKM unitarity, can write $\Gamma_{12} = \Gamma_{12}^0 + \delta\,\Gamma_{12}^0$ (responsible for ϕ_{12})

$$\Gamma_{12}^0 = -\lambda_s^2\,(\Gamma_{ss} - 2\,\Gamma_{sd} + \Gamma_{dd}), \qquad \delta\,\Gamma_{12} = 2\lambda_s\lambda_b\,(\Gamma_{sd} - \Gamma_{dd}) - \lambda_b^2\,\Gamma_{dd}$$

- $\phi_{12} = \arg(M_{12}/\Gamma_{12}) \approx -\mathrm{Im}(\delta\,\Gamma_{12}/\Gamma_{12}^0) \;\Rightarrow$

$$\phi_{12} = 2\,|\lambda_b\lambda_s|\,\sin\gamma\,\frac{\Gamma_{sd}}{\Gamma_{12}^0}\left(\frac{\Gamma_{sd}-\Gamma_{dd}}{\Gamma_{sd}} + \left|\frac{\lambda_b}{\lambda_s}\right|\cos\gamma\,\frac{\Gamma_{dd}}{\Gamma_{sd}}\right)$$

- taking $|y| = |\Gamma_{12}^0|/\Gamma$ (can ignore CPV here) $\Rightarrow$

$$|\phi_{12}| = 2\left|\frac{\lambda_b\,\lambda_s\,\sin\gamma}{y}\right| \times \left|\frac{\Gamma_{sd}}{\Gamma}\right| \times \left|\frac{\Gamma_{sd}-\Gamma_{dd}}{\Gamma_{sd}} + \left|\frac{\lambda_b}{\lambda_s}\right|\cos\gamma\,\frac{\Gamma_{dd}}{\Gamma_{sd}}\right|$$

with experimental inputs for y, CKM obtain

$$|\phi_{12}| = 0.008 \times \left|\frac{\Gamma_{sd}}{\Gamma}\right| \times \left|\frac{\Gamma_{sd}-\Gamma_{dd}}{\Gamma_{sd}} + 2.5\times10^{-4}\,\frac{\Gamma_{dd}}{\Gamma_{sd}}\right|$$

Proof that $|\Gamma_{sd}/\Gamma| < 1$ up to small $SU(3)_F$ breaking

- the two physical decay widths are $\Gamma_{1,2} = \Gamma \pm |\Gamma_{12}|$

$$\Gamma_{1,2} > 0 \quad \Rightarrow \quad |\Gamma_{12}|/\Gamma < 1$$

- consider hypothetical $D^0 - \bar{D}^0$ system with no SCS decays, and with arbitrary "CKM" suppression $\tilde{\lambda}^2$ (not λ^2), of the SM DCS decay amplitudes or operators:

$$|\Gamma_{12}| = \tilde{\lambda}^2\, 2\, \Gamma_{sd}^{SM}, \qquad \Gamma = \Gamma_{CF}^{SM} + \tilde{\lambda}^4\, (\Gamma_{DCS}^{SM}/\lambda^4)$$

- Data supports small $SU(3)_F$ breaking in DCS vs. CF:
$\Gamma_{DCS}/\lambda^4 = \Gamma_{CF}(1 + \epsilon_\Gamma)$, and small ϵ_Γ

$$\frac{|\Gamma_{12}|}{\Gamma} < 1 \quad \Rightarrow \quad \frac{\tilde{\lambda}^2\, 2\, |\Gamma_{sd}|}{\Gamma_{CF}(1 + \tilde{\lambda}^4 [1 + \epsilon_\Gamma])} < 1$$

- tightest upper bound on Γ_{sd} realized at $\tilde{\lambda}^2 \approx 1$,

$$\frac{|\Gamma_{sd}|}{\Gamma} < 1 + \epsilon_\Gamma \qquad \text{(SM)}$$

- Introduce additional $SU(3)_F$ breaking parameters:

$$\epsilon_d \equiv \frac{\Gamma_{dd} - \Gamma_{sd}}{\Gamma_{sd}}, \qquad \epsilon_s \equiv \frac{\Gamma_{ss} - \Gamma_{sd}}{\Gamma_{sd}}$$

- The bounds for CKM, y central values:

$$|\phi_{12}| < 2 \left| \frac{\lambda_b \, \lambda_s \, \sin\gamma}{y} \right| \times |\epsilon_d| \, (1 + \epsilon_\Gamma/2) = 0.008 \, |\epsilon_d| \, (1 + \epsilon_\Gamma)$$

$$|\phi_{12}| < 2 \left| \frac{\lambda_b \, \lambda_s \, \sin\gamma}{y} \right| \times |\epsilon_s| \, (1 + \epsilon_\Gamma/2) + 2 \left| \frac{\lambda_b}{\lambda_s} \sin \gamma \right| = 0.008 \, |\epsilon_s| \, (1 + \epsilon_\Gamma/2) + 0.00$$

- Expectation for ϵ_Γ, or how close is Γ_{DCS}/Γ_{CF} to $\tan^4 \theta_c = 2.9 \times 10^{-3}$?
  - time-dependent $D \to K\pi \Rightarrow \Gamma(K^+\pi^-)/\Gamma(K^-\pi^+) = (3.3 \pm 0.1) \times 10^{-3}$
  - time-integrated measurements yield ratio up to $O(10-20)\%$ corrections from interference of CF/DCS amplitudes:
    - $\Gamma(K^+\pi^-\pi^0)/\Gamma(K^-\pi^+\pi^0) \approx (2.20 \pm 0.10) \times 10^{-3}$
    - $\Gamma(K^+\pi^+\pi^-\pi^-)/\Gamma(K^-\pi^-\pi^+\pi^+) \approx (3.24^{+0.25}_{-0.22}) \times 10^{-3}$
  - data $\Rightarrow$ canonical $SU(3)_F$ breaking, $\epsilon_\Gamma \approx (10-30)\%$ makes sense - no large phase space effects

The bound, continued:

- Take $|\epsilon_s|, \quad |\epsilon_d| < 1$

$$\Rightarrow \quad |\phi_{12}| < 0.01$$

  - Violation of this bound would require both $|\epsilon_s|, \quad |\epsilon_d| > 1$. How could this happen?
  - Would require

$$\text{sign}(\Gamma_{ss}) = -\text{sign}(\Gamma_{dd}), \quad \text{and}$$

$$\frac{\Gamma_{dd}}{\Gamma_{sd}} > 2 \quad \text{and} \quad \frac{\Gamma_{ss}}{\Gamma_{sd}} < 0 \quad \text{or vice versa}$$

  In this case still expect $|\epsilon_s|, \quad |\epsilon_d| = O(1)$, and $|\phi_{12}| \lesssim 0.01$

  - ultimately, will be able to constrain $|\epsilon_s|, \quad |\epsilon_d|$ by considering sums over exclusive state in Γ_{xy}

- An OPE analysis yields $\phi_{12} << 0.01$ for dim-6,7 operators Borowski et al, however the authors have suggested that higher dimensional operators may yield $\phi_{12} \sim 10^{-2}$

Updated bounds on $\sin\ \phi_{12}$ from experiment **thanks to Rolf Andreasson and Mike Sokoloff for fits**

Updated bounds on CPV in SCS $D^0 \to K^+K^-, \ \pi^+\pi^-$ decays

The time-integrated CP asymmetry

$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

- Expanding to leading order in subleading amplitudes, mass difference, width difference
  - at the B-factories: Grossman, A.K., Nir

$$a_f = a_f^{\rm dir} + a^{\rm ind}, \quad a^{\rm ind} = a^m + a^i$$

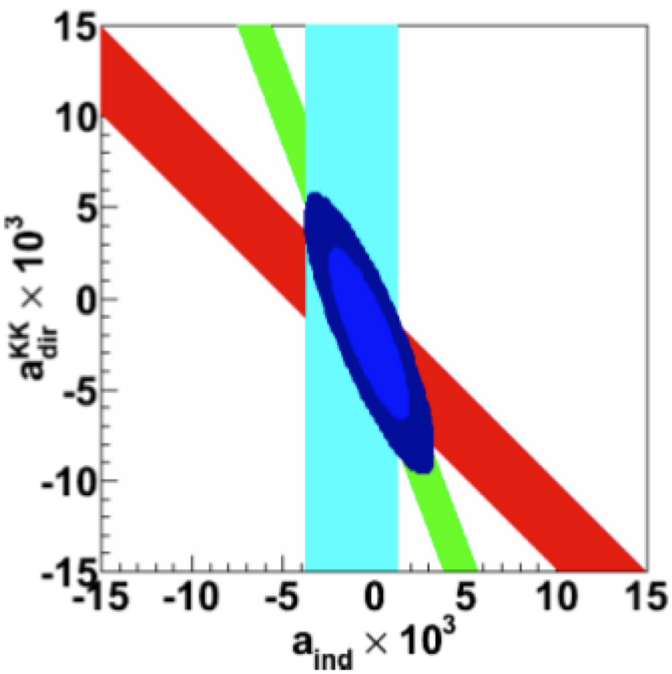
  - at CDF (due to cut on proper decay time):

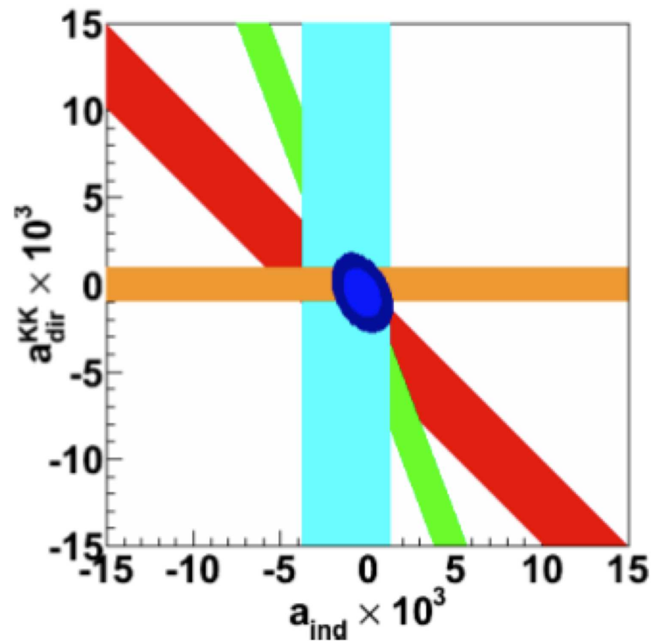
$$a_f = a_f^{\rm dir} + 2.40\, a^{\rm ind} \quad (\pi^+\pi^-)\,; \quad a_f = a_f^{\rm dir} + 2.65\, a^{\rm ind} \quad (K^+K^-)$$

- $a^{\rm dir}$ is direct CP violation
- a^m: CP violation in mixing CPVMIX
- a^i: CP violation in the interference of decays with and without mixing CPVINT
- the total indirect CP asymmetry $a^{\rm ind}$ is universal - independent of final state. Note $a^{\rm ind} = \Delta Y$ (the time-dependent CP asymmetry)

Separating indirect and direct CP violation

Combine the Belle, BaBar, and CDF KK, $\pi\pi$ time-integrated measurements a_f, with the Belle/BaBar time-dependent measurement $\Delta Y = a^{\mathrm{ind}}$





left: ΔY (aqua), a_f BaBar/Belle (red); a_f CDF (green).
right: $|a^{\mathrm{dir}}_{KK,\pi\pi}| < 0.2\,\%$ for models with negligible new weak phases in decay, e.g., SM

- without imposing any theoretical constraints on $a^{\rm dir}$ obtain

$$a^{\rm ind} = -0.026 \pm 0.14\%; \quad \text{compared to } \Delta Y = 0.123 \pm 0.248\%$$

$$a^{\rm dir}(\pi\pi) = 0.24 \pm 0.36\%, \quad a^{\rm dir}(KK) = 0.19 \pm 0.31\%$$

- from an analysis of $a^{\rm dir}(KK, \pi\pi)$ in the SM
  - at leading power: naive factorization + $O(\alpha_s)$ corrections $a^{\rm dir} = O(10^{-4})$
  - power corrections, e.g., annihilation, FSI, can enhance $a^{\rm dir}$ by $O(10)$
  - therefore, expect $|a^{\rm dir}| < 0.2\%$ in the SM and in models with no new weak phases in decay
    - theoretical uncertainty $\Rightarrow$ the window for NP in $a^{\rm dir}$ is rapidly closing
- adding this constraint to the time-integrated and time-dependent measurements

$$\Rightarrow \quad a^{\rm ind} = (-0.023 \pm 0.09)\%!$$

in models with no new weak phases in decay. The small error in this case is due to the CDF measurements

Updated experimental bounds on $\sin\,\phi_{12}$

- The mixing observables

$$\phi, \quad |q/p|, \quad x = \frac{m_2 - m_1}{\Gamma}, \quad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

ϕ is the phase difference between mixing, decay amps. For example,

$$a_{\mathrm{SL}} = 2(|q/p| - 1)$$

$$a^m(KK, \pi\pi) = -\frac{y}{2}\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right), \quad a^i(KK, \pi\pi) = \frac{x}{2}\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)$$

- in absence of new weak phases in decay, $\phi_{12} \neq 0$ is the only source of CPV. Therefore, CPVMIX (a^m) and CPVINT (a^i) are related (Grossman, Nir, Perez; A.K. and M. Sokoloff)

- obtain relations between theory parameters ϕ_{12}, x_{12}, y_{12} and the mixing observables $\phi, |q/p|, x, y$. For example,

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

  - given current bounds on direct CP asymmetries, this relation also holds to good approximation when allowing for new weak phases in decay

Strategy

- HFAG has fit the observables $\phi, |q/p|, x, y$ to the $D-\overline{D}$ mixing and CPV data
- they have not included the time-integrated data for K^+K^-, $\pi^+\pi^-$ (pre-FPCP)
- have obtained their fit with error matrix, for ΔY subtracted thanks to Alan Schwartz for providing this info
- have added the new average for $a^{\rm ind} = \Delta Y$, without and with the $a^{\rm dir}$ constraint, as an additional independent observable
- using the relations between ϕ_{12}, x_{12}, y_{12} and the mixing observables $\phi, |q/p|, x, y$ and $a^{\rm ind}$, we have fit for ϕ_{12}, x_{12}, y_{12}, using this error matrix

Results for ϕ_{12}^{exp}

- Without imposing $a^{\mathrm{dir}}(KK,\pi\pi)$ constraint, obtain

$$\phi_{12} = 0.03 \pm 0.11 \ [\mathrm{rad}]$$

  for no new weak phases in CF/DCS decays,

$$\phi_{12} = 0.07 \pm 0.14 \ [\mathrm{rad}]$$

  allowing for new weak phases in CF/DCS decays.

- Imposing $a^{\mathrm{dir}}(KK,\pi\pi) < 0.002$, corresponding to models with no new weak phases in SCS decays, and for no new weak phases in CF/DCS decays, obtain

$$\phi_{12} = 0.03 \pm 0.09 \ [\mathrm{rad}]$$

  This applies to a wide class of models which do not have new weak phases in SCS, CF, and DCS decays

- used parabolic errors. robust treatment with non-parabolic errors to be carried out by HFAG, taking into account the model-independent relations and time-integrated CPV data

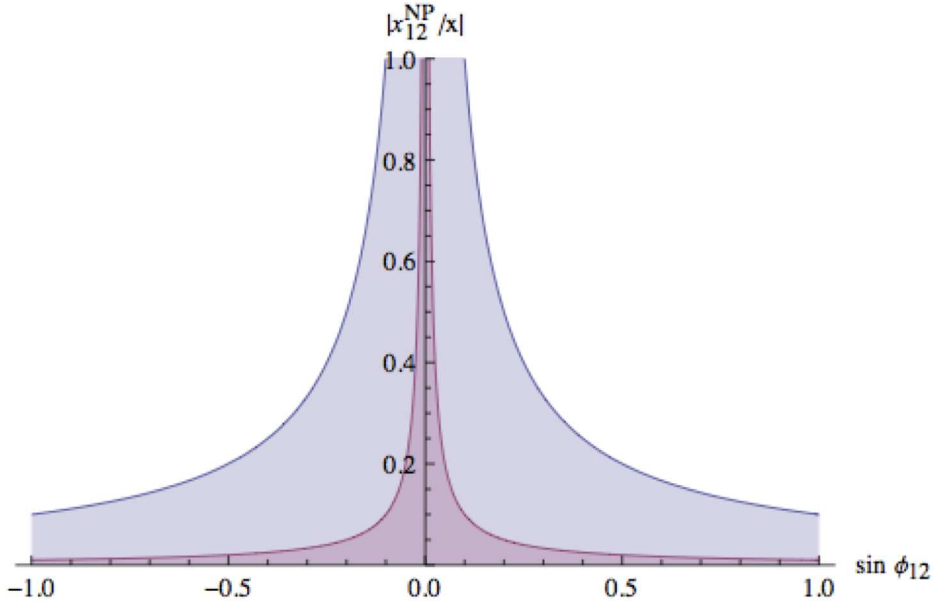
Conclusion

- in the SM $\phi_{12} \sim 0.01$
  - indirect CP asymmetries are $O(x_{12} \sin \phi_{12}) < 10^{-4}$ in the SM
- updated fit to HFAG outputs + $a^{\rm ind}(KK, \pi\pi)$ yields

$$\phi_{12} \sim \pm 0.10 \quad \text{at } 1\sigma$$

  so plenty of room for NP
- writing $M_{12} = M_{12}^{\rm SM} + M_{12}^{\rm NP}$ the bounds imply (taking $M^{\rm SM}$ real, $\Gamma_{12} = \Gamma_{12}^{\rm SM}$)

$$\left| \frac{\mathrm{Im}(M_{12}^{\rm NP})}{M_{12}} \right| = |\sin \phi_{12}| \lesssim 0.10$$



- all indirect CP asymmetries (time-dependent, time-integrated, SCS, CF/DCS) are $\propto x_{12} \sin \phi_{12}$

- allowing $x_{12}^{\rm NP} \sim x_{12}^{\rm exp}$ and taking into account the current situation

$$x_{12} \sin \phi_{12} \lesssim 10^{-3}$$

  can represent the allowed region of $x_{12}^{\rm NP}$ vs. $\sin \phi_{12}^{\rm NP}$ as above Gedalia et al., thanks to G. Perez for updating the plot,

- the dark region corresponds to the SM bound $x_{12} \sin \phi_{12} \lesssim 10^{-4}$, and is the region in which sensitivity to NP would be lost