Theoretical implications of CP-violation in charm

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Disclaimer:

"It is always wise to look ahead, but difficult to look further than you can see."

Winston Churchill

Introduction

★ Fundamental problem: observation of CP-violation in up-quark sector!

★ Possible sources of CP violation in charm transitions:

★ CPV in $\Delta c = 1$ decay amplitudes ("direct" CPV)

$$\Gamma(D \to f) \neq \Gamma(CP[D] \to CP[f])$$

★ CPV in $D^0 - \overline{D^0}$ mixing matrix ($\Delta c = 2$):

$$\left|D_{1,2}\right\rangle = p\left|D^0\right\rangle \pm q\left|\overline{D^0}\right\rangle \Rightarrow |D_{CP\pm}\rangle = \frac{1}{\sqrt{2}}\left(|D^0\rangle \pm \left|\overline{D}^0\right\rangle\right)$$

$$R_m^2 = |q/p|^2 = \left|\frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta m - (i/2)\Delta\Gamma}\right|^2 = 1 + A_m \neq 1$$

★ CPV in the interference of decays with and without mixing

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = R_m e^{i(\phi+\delta)}\left|\frac{\overline{A}_f}{A_f}\right|$$

★ One can separate various sources of CPV by customizing observables

CP-violation I: indirect

★ Indirect CP-violation manifests itself in $D\overline{D}$-oscillations

★ "Experimental" mass and lifetime differences of mass eigenstates...

$$x_D = \frac{M_2 - M_1}{\Gamma_D}, \quad y_D = \frac{\Gamma_2 - \Gamma_1}{2\Gamma_D}$$

★ ...can be calculated as real and imaginary parts of a correlation function

$$y_{\rm D} = \frac{1}{2M_{\rm D}\Gamma_{\rm D}} \, {\rm Im} \, \langle \overline{D^0} | \, i \int {\rm d}^4 x \, T \left\{ \mathcal{H}_w^{|\Delta C|=1}(x) \, \mathcal{H}_w^{|\Delta C|=1}(0) \right\} | D^0 \rangle$$

bi-local time-ordered product

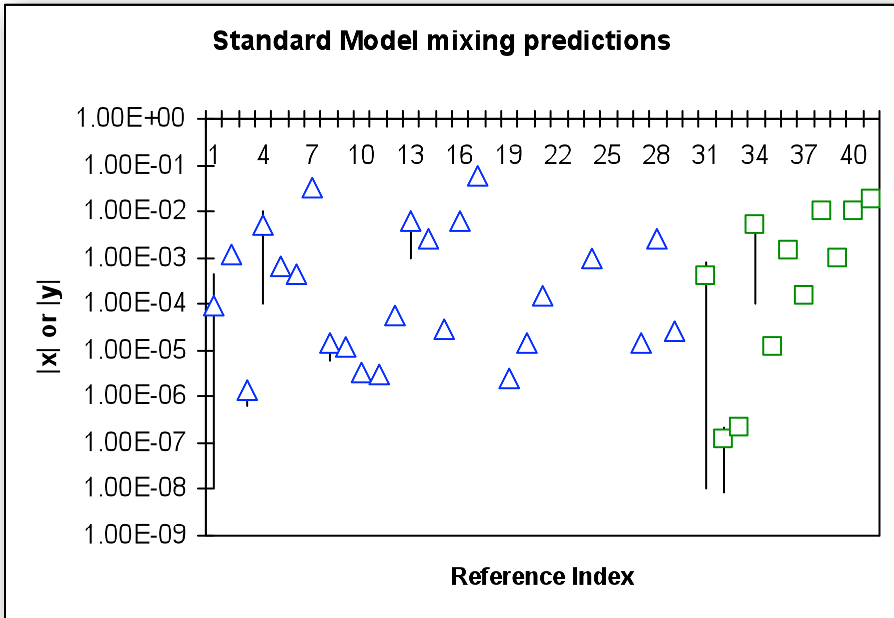
$$x_{\rm D} = \frac{1}{2M_{\rm D}\Gamma_{\rm D}} \, {\rm Re} \left[2 \langle \overline{D^0} | H^{|\Delta C|=2} | D^0 \rangle + \langle \overline{D^0} | \, i \int {\rm d}^4 x \, T \left\{ \mathcal{H}_w^{|\Delta C|=1}(x) \, \mathcal{H}_w^{|\Delta C|=1}(0) \right\} | D^0 \rangle \right]$$

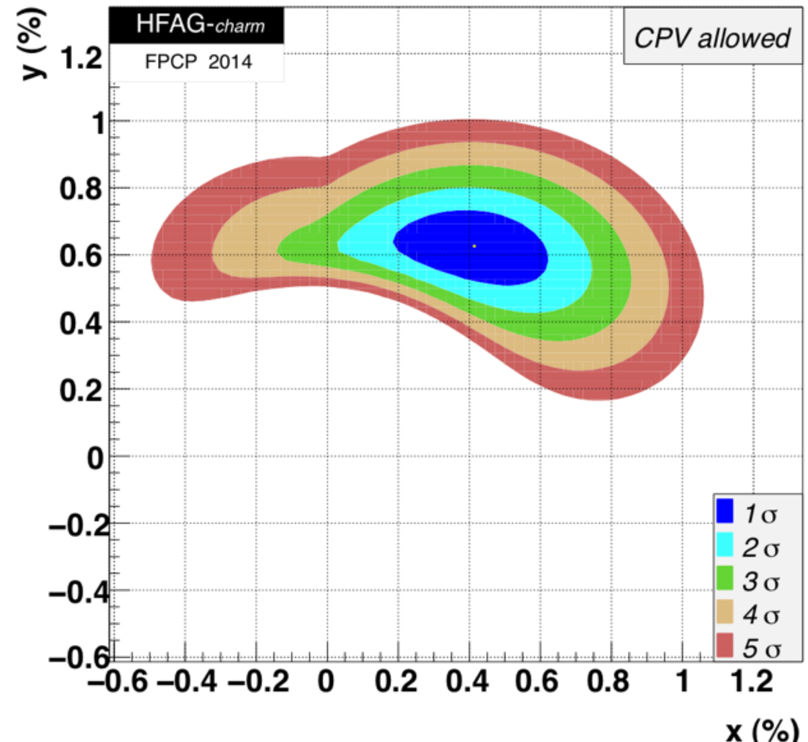
local operator
(b-quark, NP): small?

bi-local time-ordered product

★ Theoretically, y_D is dominated by long-distance SM-dominated effects
★ CP-violating phases can appear from subleading local SM or NP operators

CP-violation I: indirect





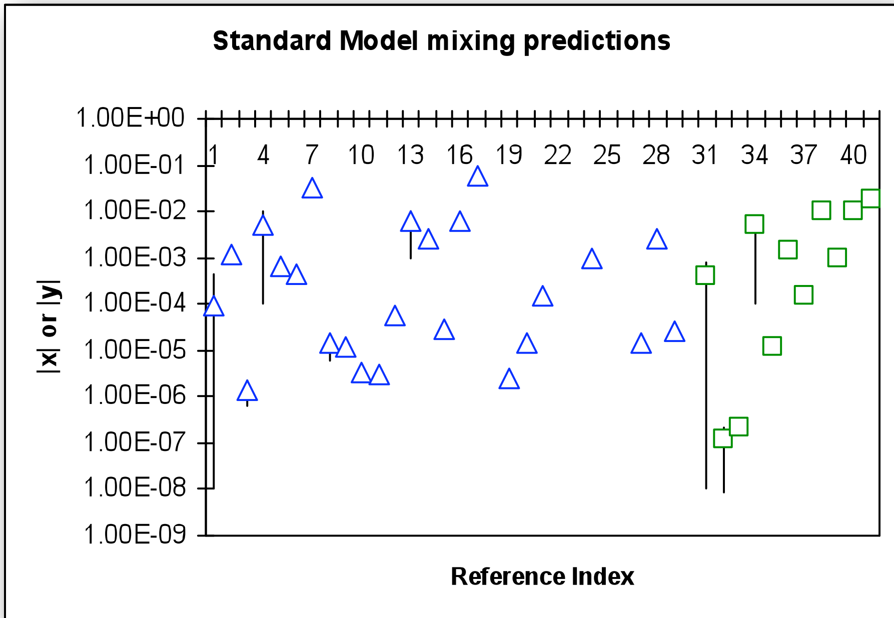
$$x_D = 0.41^{+0.14}_{-0.15}\%, \quad y_D = 0.63^{+0.07}_{-0.08}\%$$

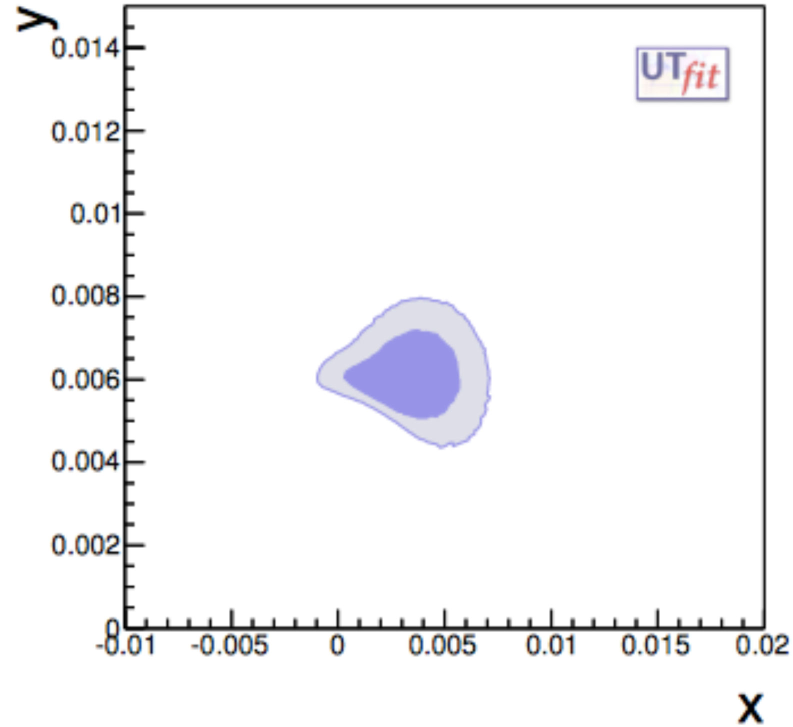
★ It seems like $x_D \sim y_D \sim O(1\%)$ - consistent with SM?

★ SM CP-violating phase is $\arg(V_{cb}V_{ub}) \sim \gamma$

★ SM CP-violating amplitude is always suppressed by $|V_{cb}V_{ub}/V_{cs}V_{us}| \sim O(10^{-3})$

CP-violation I: indirect





UTFit JHEP 1403 (2014) 123

$$x_D = 0.41^{+0.14}_{-0.15}\%, \quad y_D = 0.63^{+0.07}_{-0.08}\%$$

- ★ It seems like $x_D \sim y_D \sim O(1\%)$ - consistent with SM?
- ★ SM CP-violating phase is $\arg(V_{cb}V_{ub}) \sim \gamma$
- ★ SM CP-violating amplitude is always suppressed by $|V_{cb}V_{ub}/V_{cs}V_{us}| \sim O(10^{-3})$

CP-violation I: indirect

★ Indirect CP-violation manifests itself in $D\bar{D}$-oscillations

- see time development of a D-system:

$$i\frac{d}{dt}|D(t)\rangle = \left(M - \frac{i}{2}\Gamma\right)|D(t)\rangle$$

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

★ Define "theoretical" mixing parameters

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

★ Assume that direct CP-violation is absent ($\mathrm{Im}\,(\Gamma_{12}^*\bar{A}_f/A_f) = 0$, $|\bar{A}_f/A_f| = 1$)

- can relate x, y, φ, |q/p| to x_{12}, y_{12} and φ_{12}

"superweak limit"

$$xy = x_{12}y_{12}\cos\phi_{12}, \qquad x^2 - y^2 = x_{12}^2 - y_{12}^2,$$
$$(x^2 + y^2)|q/p|^2 = x_{12}^2 + y_{12}^2 + 2x_{12}y_{12}\sin\phi_{12},$$
$$x^2\cos^2\phi - y^2\sin^2\phi = x_{12}^2\cos^2\phi_{12}.$$

★ Four "experimental" parameters related to three "theoretical" ones

- a "constraint" equation is possible

CP-violation I: indirect

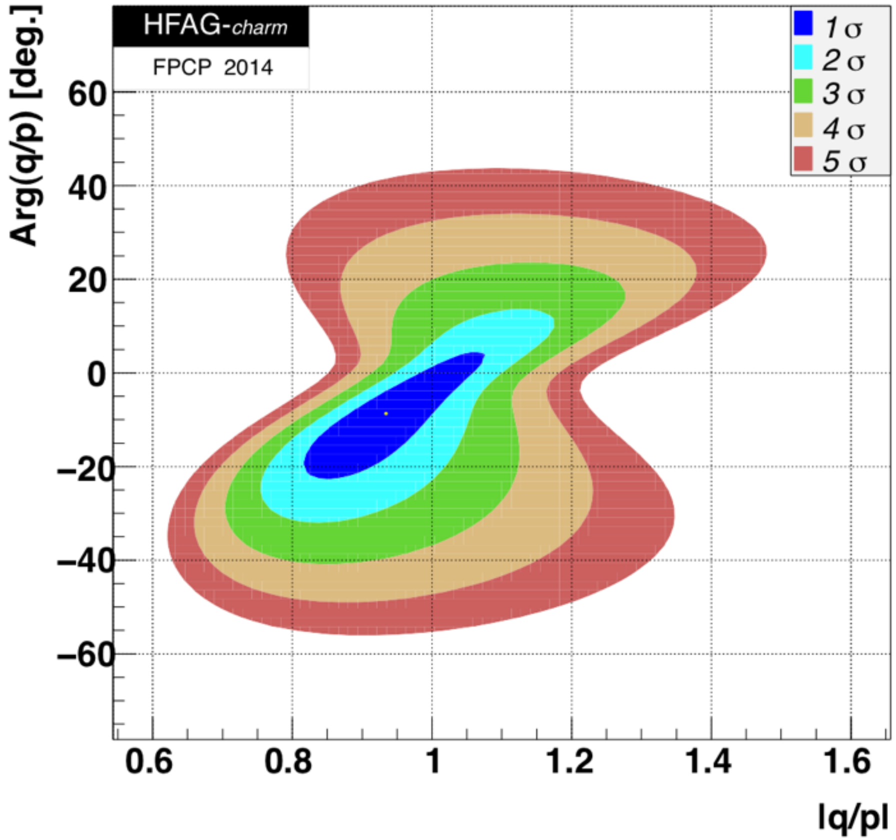
★ Relation; data from HFAG's compilation

$$\frac{x}{y} = \frac{1-|q/p|}{\tan\phi} = -\frac{1}{2}\frac{A_m}{\tan\phi}$$

- it might be experimentally $x_D < y_D$
- this has implications for NP searches in charm CP-violating asymmetries!

- that is, if $|M_{12}| < |\Gamma_{12}|$:

$$\begin{aligned} x/y &= 2\,|M_{12}/\Gamma_{12}|\cos\phi_{12}, \\ A_m &= 4\,|M_{12}/\Gamma_{12}|\sin\phi_{12}, \\ \phi &= -2\,|M_{12}/\Gamma_{12}|^2\sin 2\phi_{12}. \end{aligned}$$



Note: CPV is suppressed even if M_{12} is all NP!!!

Bergmann, Grossman, Ligeti, Nir, AAP PL B486 (2000) 418

★ With available experimental constraints on x, y, and q/p, one can bound WCs of a generic NP Lagrangian -- bound any high-scale model of NP

Generic restrictions on NP from $D\bar{D}$-mixing

★ Comparing to experimental value of x, obtain constraints on NP models
- assume x is dominated by the New Physics model
- assume no accidental strong cancellations b/w SM and NP

$$\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} z_i(\mu) Q_i'$$

$$\begin{aligned} Q_1^{cu} &= \bar{u}_L^\alpha \gamma_\mu c_L^\alpha \bar{u}_L^\beta \gamma^\mu c_L^\beta, \\ Q_2^{cu} &= \bar{u}_R^\alpha c_L^\alpha \bar{u}_R^\beta c_L^\beta, \\ Q_3^{cu} &= \bar{u}_R^\alpha c_L^\beta \bar{u}_R^\beta c_L^\alpha, \end{aligned} + \left\{ \begin{matrix} L \\ \updownarrow \\ R \end{matrix} \right\} + \begin{aligned} Q_4^{cu} &= \bar{u}_R^\alpha c_L^\alpha \bar{u}_L^\beta c_R^\beta, \\ Q_5^{cu} &= \bar{u}_R^\alpha c_L^\beta \bar{u}_L^\beta c_R^\alpha, \end{aligned}$$

★ ... which are

$$|z_1| \lesssim 5.7 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$
$$|z_2| \lesssim 1.6 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$
$$|z_3| \lesssim 5.8 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$
$$|z_4| \lesssim 5.6 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$
$$|z_5| \lesssim 1.6 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2.$$

New Physics is either at a very high scales

tree level: $\Lambda_{NP} \geq (4-10) \times 10^3 \ \mathrm{TeV}$

loop level: $\Lambda_{NP} \geq (1-3) \times 10^2 \ \mathrm{TeV}$

or have highly suppressed couplings to charm!

Gedalia, Grossman, Nir, Perez
Phys.Rev.D80, 055024, 2009

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
Phys. Rev. D76:095009, 2007

★ Constraints on particular NP models available

CP-violation I: indirect

★ Assume that direct CP-violation is absent $(\mathrm{Im}\,(\Gamma_{12}^* \bar{A}_f/A_f) = 0, \;\; |\bar{A}_f/A_f| = 1)$

- experimental constraints on x, y, φ, |q/p| exist
- can obtain generic constraints on Im parts of Wilson coefficients

$$\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} z_i(\mu) Q_i'$$

★ In particular, from $x_{12}^{\rm NP} \sin \phi_{12}^{\rm NP} \lesssim 0.0022$

$$\mathcal{I}m(z_1) \lesssim 1.1 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\;TeV}\right)^2,$$
$$\mathcal{I}m(z_2) \lesssim 2.9 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\;TeV}\right)^2,$$
$$\mathcal{I}m(z_3) \lesssim 1.1 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\;TeV}\right)^2,$$
$$\mathcal{I}m(z_4) \lesssim 1.1 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\;TeV}\right)^2,$$
$$\mathcal{I}m(z_5) \lesssim 3.0 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\;TeV}\right)^2.$$

New Physics is either at a very high scales

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loop level: $\Lambda_{NP} \geq (1-3) \times 10^2$ TeV

or have highly suppressed couplings to charm!

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Phys.Rev.D80, 055024, 2009

Bigi, Blanke, Buras, Recksiegel,
JHEP 0907:097, 2009

★ Constraints on particular NP models possible as well

CP-violation I: beyond "superweak"

★ Look at parameterization of CPV phases; separate absorptive and dispersive

Grossman, Kagan, Perez, Silvestrini, AAP

$$\lambda_f^2 = \frac{2M_{12}^* - i\Gamma_{12}^*}{2M_{12} - i\Gamma_{12}} \left(\frac{\overline{A}_f}{A_f}\right)^2$$

- consider f= CP eigenstate, can generalize later: $\lambda_{CP}^2 = R_m^2 e^{2i\phi}$

$$\phi^M_{12\,f} = \frac{1}{2} \arg\left[\frac{M_{12}}{M_{12}^*}\left(\frac{A_f}{\overline{A}_f}\right)^2\right] \qquad \phi^\Gamma_{12\,f} = \frac{1}{2} \arg\left[\frac{\Gamma_{12}}{\Gamma_{12}^*}\left(\frac{A_f}{\overline{A}_f}\right)^2\right]$$

- CP-violating phase for the final state f is then

$$\phi_{12} = \phi^M_{12\,f} - \phi^\Gamma_{12\,f}$$

★ Can we put a Standard Model theoretical bound on $\phi^M_{12\,f}$ or $\phi^\Gamma_{12\,f}$?

CP-violation I: beyond "superweak"

★ Let us define convention-independent universal CPV phases. First note that

- for the absorptive part: $\Gamma_{12} = \Gamma_{12}^0 + \delta\Gamma_{12}$

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

$$\delta\Gamma_{12} = 2\lambda_b\lambda_s(\Gamma_{sd} - \Gamma_{ss}) + O(\lambda_b^2)$$

- … and similarly for the dispersive part: $M_{12} = M_{12}^0 + \delta M_{12}$

★ CP-violating mixing phase can then be written as

$$\phi_{12} = \arg\frac{M_{12}}{\Gamma_{12}} = \mathrm{Im}\left(\frac{\delta M_{12}}{M_{12}^0}\right) - \mathrm{Im}\left(\frac{\delta\Gamma_{12}}{\Gamma_{12}^0}\right) \equiv \phi_{12}^M - \phi_{12}^\Gamma$$

★ These phases can then be constrained; e.g. the absorptive phase

$$|\phi_{12}^\Gamma| = 0.009 \times \frac{|\Gamma_{sd}|}{\Gamma} \times \left|\frac{\Gamma_{sd} - \Gamma_{dd}}{\Gamma_{sd}}\right| < 0.01$$

Grossman, Kagan, Perez, Silvestrini, AAP

Other observables: untagged asymmetries?

A.A.P., PRD69, 111901(R), 2004

★ Look for CPV signals that are

- first order in CPV parameters
- do not require flavor tagging (for D^0)

★ Consider the final states that can be reached by both D^0 and $\overline{D^0}$, but are not CP eigenstates ($\pi\rho$, KK^*, $K\pi$, $K\rho$, …)

$$A_{CP}^U(f) = \frac{\Sigma_f - \Sigma_{\bar{f}}}{\Sigma_f + \Sigma_{\bar{f}}} \quad \text{where} \quad \Sigma_f = \Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)$$

★ For a CF/DCS final state $K\pi$, the time-integrated asymmetry is simple

$$A_{CP}^U\left(K^+\pi^-\right) = -y \sin\delta_{K\pi} \sin\phi \sqrt{R_{K\pi}}$$

($<10^{-4}$ for NP)

★ For a SCS final state $\rho\pi$, neglecting direct CPV contribution,

$$A_{CP}^U\left(\rho^+\pi^-\right) = -y \sin\delta_{\rho\pi} \sin\phi \sqrt{R_{\rho\pi}}$$

($<10^{-2}$ for NP)

Note: a "theory-free" relation!

CP-violation II: direct

★ IDEA: consider the DIFFERENCE of decay rate asymmetries: $D \to \pi\pi$ vs $D \to KK$!
For each final state the asymmetry

D^0: no neutrals in the final state!

$$a_f = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})} \quad \Rightarrow \quad a_f = a_f^d + a_f^m + a_f^i$$

direct — mixing — interference

★ A reason: $a^m_{KK}=a^m_{\pi\pi}$ and $a^i_{KK}=a^i_{\pi\pi}$ (for CP-eigenstate final states), so, ideally, mixing asymmetries cancel!

$$a_f^d = 2r_f \sin\phi_f \sin\delta_f$$

★ ... and the resulting DCPV asymmetry is $\Delta a_{CP} = a^d_{KK} - a^d_{\pi\pi} \approx 2a^d_{KK}$ (double!)

$$A_{KK} = \frac{G_F}{\sqrt{2}}\lambda\left[(T+E+P_{sd}) + a\lambda^4 e^{-i\gamma}P_{bd}\right]$$

$$A_{\pi\pi} = \frac{G_F}{\sqrt{2}}\lambda\left[(-(T+E)+P_{sd}) + a\lambda^4 e^{-i\gamma}P_{bd}\right]$$

★ ... so it is doubled in the limit of $SU(3)_F$ symmetry

SU(3) is badly broken in D-decays
e.g. Br(D → KK) ~ 3 Br(D → ππ)

Experiment?

★ Experiment: the difference of CP-asymmetries: $\Delta a_{CP} = a_{CP,KK} - a_{CP,\pi\pi}$

★ Earlier results (before 2013):

Experiment	ΔA_{CP}
LHCb	$(-0.82 \pm 0.21 \pm 0.11)\%$
CDF	$(-0.62 \pm 0.21 \pm 0.10)\%$
Belle	$(-0.87 \pm 0.41 \pm 0.06)\%$
BaBar	$(+0.24 \pm 0.62 \pm 0.26)\%$

Looks like CP is broken in charm transitions! Now what?

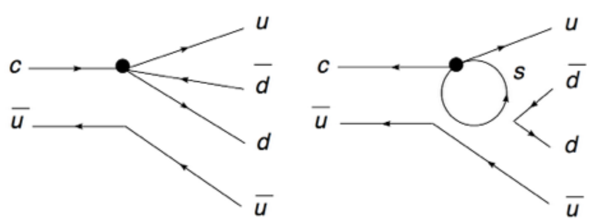
Is it Standard Model or New Physics??

★ Is it Standard Model or New Physics? Theorists used to say...

Naively, any CP-violating signal in the SM will be small, at most $O(V_{ub}V_{cb}^*/V_{us}V_{cs}^*) \sim 10^{-3}$
Thus, O(1%) CP-violating signal can provide a "smoking gun" signature of New Physics

...what do you say now?

★ assuming SU(3) symmetry, $a_{CP}(\pi\pi) \sim a_{CP}(KK) \sim 0.4\%$. Is it 1% or 0.1%?
★ let us try Standard Model
- need to estimate size of penguin/penguin contractions vs. tree



- unknown penguin enhancement (similar to $\Delta I = 1/2$)
  - SU(3) analysis: some ME are enhanced

  Golden & Grinstein PLB 222 (1989) 501;Pirtshalava & Uttayarat 1112.5451

  - unusually large $1/m_c$ corrections

  Isidori et al PLB 711 (2012) 46; Brod et al 1111.5000

  - no assumptions, flavor-flow diagrams

  Broad et al 1203.6659; Bhattacharya et al PRD 85 (2012) 054014;
  Cheng & Chiang 1205.0580

Is it a penguin or a tree?

Without QCD

With QCD

New Physics: operator analysis

★ Factorizing decay amplitudes, e.g.

$$\mathcal{H}^{\rm eff-NP}_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_{i=1,2,5,6} \sum_q (C_i^q Q_i^q + C_i^{q\prime} Q_i^{q\prime}) + \frac{G_F}{\sqrt{2}} \sum_{i=7,8} (C_i Q_i + C_i' Q_i') + {\rm H.c.}$$

$$Q_1^q = (\bar u q)_{V-A}\,(\bar q c)_{V-A}$$

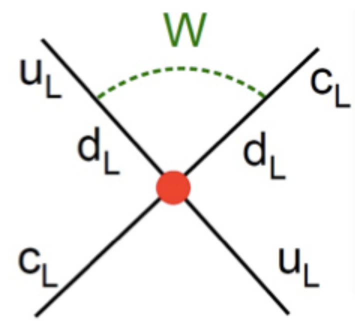
$$Q_2^q = (\bar u_\alpha q_\beta)_{V-A}\,(\bar q_\beta c_\alpha)_{V-A}$$

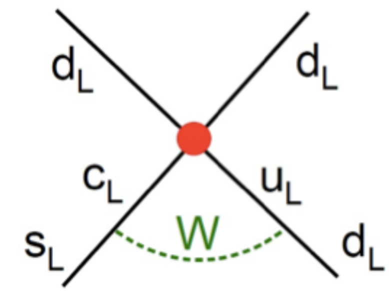
$$Q_5^q = (\bar u c)_{V-A}\,(\bar q q)_{V+A}$$

$$Q_6^q = (\bar u_\alpha c_\beta)_{V-A}\,(\bar q_\beta q_\alpha)_{V+A}$$

$$Q_7 = -\frac{e}{8\pi^2}\, m_c\, \bar u \sigma_{\mu\nu}(1+\gamma_5) F^{\mu\nu} c$$

$$Q_8 = -\frac{g_s}{8\pi^2}\, m_c\, \bar u \sigma_{\mu\nu}(1+\gamma_5) T^a G_a^{\mu\nu} c$$





Z. Ligeti, CHARM-2012

★ one can fit to ε′/ε and mass difference in D-anti-D-mixing

Gedalia, et al, arXiv:1202.5038

- LL are ruled out
- LR are borderline
- RR and dipoles are possible

Allowed	Ajar	Disfavored
$Q_{7,8}$, $Q'_{7,8}$, $\forall f\ Q^{f\prime}_{1,2}$, $Q^{(c-u,b,0)\prime}_{5,6}$	$Q^{(c-u,8d,b,0)}_{1,2}$, $Q^{(0)}_{5,6}$, $Q^{(8d)\prime}_{5,6}$	$Q^{s-d}_{1,2}$, $Q^{(s-d)\prime}_{5,6}$, $Q^{s-d,c-u,8d,b}_{5,6}$

Constraints from particular models also available

Experiment again?

★ Experiment: the difference of CP-asymmetries: $\Delta a_{CP} = a_{CP,KK} - a_{CP,\pi\pi}$

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Looks like CP is broken in charm transitions! Now what?

★ Recent results (after 2013):

$$\Delta a_{CP} = (+0.14 \pm 0.16(\text{stat}) \pm 0.08(\text{syst}))\,\%$$
$$a_{CP,KK} = (-0.06 \pm 0.15(\text{stat}) \pm 0.10(\text{syst}))\,\%$$
$$a_{CP,\pi\pi} = (-0.20 \pm 0.19(\text{stat}) \pm 0.10(\text{syst}))\,\%$$

LHCb arXiv:1405.2797

Is it NP or SM? Doesn’t look like NP is needed to explain the result.

"Having nothing, nothing can he lose."

William Shakespeare, "Henry VI"

Future: lattice to the rescue*?

★ There are methods to compute decays on the lattice (Lellouch-Lüscher)
- calculation of scattering of final state particles in a finite box
- matching resulting discrete energy levels to decaying particle
- reasonably well developed for a single-channel problems (e.g. kaon decays)

★ Can these methods be generalized to D-decays?
- make D-meson slightly lighter, $m_D < 4\, m_\pi$
- assume G-parity and consider scattering of two pions and two kaons in a box with SM scattering energy

$$2m_\pi < 2m_K < E^* < 4m_\pi$$

Hansen, Sharpe
PRD86, 016007 (2012)

- only four possible scattering events: $\pi\pi \to \pi\pi$, $\pi\pi \to KK$, $KK \to \pi\pi$, $KK \to KK$
- couple the two by adding weak part to the strong Hamiltonian $\mathcal{H}(x) \to \mathcal{H}(x) + \lambda \mathcal{H}_W(x)$

★ Application of this approach to calculate lifetime difference is not trivial!!!
- need to consider other members of SU(3) octet
- need to consider 4π states that mix with $\pi\pi$ + others
- need to consider 3-body and excited light-quark states

* See "**panacea**": In Greek mythology, **Panacea** (Greek *Πανάκεια*, **Panakeia**) was a goddess of Universal remedy.

Future: CP-violation in charmed baryons

- Other observables can be constructed for baryons, e.g.

$$A(\Lambda_c \to N\pi) = \bar{u}_N(p,s)\left[A_S + A_P\gamma_5\right]u_{\Lambda_c}(p_\Lambda, s_\Lambda)$$

These amplitudes can be related to "asymmetry parameter" $\alpha_{\Lambda_c} = \dfrac{2\,\mathrm{Re}\left(A_S^* A_P\right)}{\left|A_S\right|^2 + \left|A_P\right|^2}$

... which can be extracted from $\dfrac{dW}{d\cos\vartheta} = \dfrac{1}{2}\left(1 + P\alpha_{\Lambda_c}\cos\vartheta\right)$

Same is true for $\overline{\Lambda}_c$-decay

If CP is conserved $\alpha_{\Lambda_c} \overset{CP}{\Rightarrow} -\overline{\alpha}_{\Lambda_c}$, thus CP-violating observable is

$$A_f = \frac{\alpha_{\Lambda_c} + \overline{\alpha}_{\Lambda_c}}{\alpha_{\Lambda_c} - \overline{\alpha}_{\Lambda_c}}$$

FOCUS[2006]: $A_{\Lambda\pi}$=-0.07±0.19±0.24

Rare radiative decays of charm

★ Can radiative charm decays help with Δa_{CP}?

★ In many NP models, there is a link between chromomagnetic and electric-dipole operators

Isidori, Kamenik (12)
Lyon, Zwicky (12)

$$\mathcal{Q}_8 = \frac{m_c}{4\pi^2} \bar{u}_L \sigma_{\mu\nu} T^a g_s G_a^{\mu\nu} c_R$$

$$\mathcal{Q}_7 = \frac{m_c}{4\pi^2} \bar{u}_L \sigma_{\mu\nu} Q_u e F^{\mu\nu} c_R$$

Same is true for operators of opposite chirality as well

★ There are many operators that can generate Δa_{CP}

Giudice, Isidori, Paradisi (12)

- one possibility is that NP affects Q_8 the most; the asymmetry then

$$|\Delta a_{CP}^{\rm NP}| \approx -1.8 |{\rm Im}[C_8^{\rm NP}(m_c)]|$$

- e.g. in SUSY, gluino-mediated amplitude satisfies $C_7^{\rm SUSY}(m_{\rm SUSY}) = (4/15) C_8^{\rm SUSY}(m_{\rm SUSY})$
- then at the charm scale,

$$|{\rm Im}[C_7^{\rm NP}(m_c)]| = (0.2 - 0.8) \times 10^{-2}$$

$$|C_7^{\rm SM-eff}(m_c)| = (0.5 \pm 0.1) \times 10^{-2}$$

What about LD effects?

CP-violation in radiative decays of charm

★ Probing a_{CP} in radiative D-decays can probe Im C_7 → Im C_8 → Δa_{CP}

- problem is, radiative decays are dominated by LD effects

Isidori, Kamenik (12)

$$\Gamma(D \to V\gamma) = \frac{m_D^3}{32\pi}\left(1 - \frac{m_V^2}{m_D^2}\right)^3 \left[|A_{PV}|^2 + |A_{PC}|^2\right]$$

★ CP-violating asymmetry in radiative transitions would be

$$|a_{(\rho,\omega)\gamma}|^{\max} = 0.04(1)\left|\frac{\mathrm{Im}[C_7(m_c)]}{0.4 \times 10^{-2}}\right| \times \times \left[\frac{10^{-5}}{\mathcal{B}(D \to (\rho,\omega)\gamma)}\right]^{1/2} \lesssim 10\% \ .$$

★ Better go off-resonance (consider $K^+K^-\gamma$) or even $h^+h^-\mu^+\mu^-$ final states

- the LD effects would be smaller, but the rate goes down as well

Isidori, Kamenik (12)
Cappiello, Cata, D'Ambrosio (12)

Things to take home

- Computation of charm amplitudes is a difficult task
  - no dominant heavy dof, as in beauty decays
  - light dofs give no contribution in the flavor SU(3) limit
  - D-mixing is a second order effect in SU(3) breaking ($x, y \sim 1\%$ in the SM)
- For indirect CP-violation studies
  - constraints on Wilson coefficients of generic operators are possible, point to the scales much higher than those directly probed by LHC
  - consider new parameterizations that go beyond the “superweak” limit
- For direct CP-violation studies
  - unfortunately, large DCPV signal is no more; need more results in individual channels, especially including baryons
  - hit the “brown muck”: future observation of DCPV does not give easy interpretation in terms of fundamental parameters
  - need better calculations: lattice?
- Lattice calculations can, in the future, provide a result for a_{CP}!
- Need to give more thought on how large SM CPV can be…

"I'm looking for a lot of men who have an infinite capacity to not know what can't be done."

Henry Ford

"Strong reasons make strong actions."

William Shakespeare, King John (1598), Act III, scene 4, line 182


EXTRA!

Experimental analyses of mixing

★ In principle, can extract mixing (x,y) and CP-violating parameters (A_m, φ)

★ In particular, time-dependent $D^0(t) \to K^+\pi^-$ analysis

$$\Gamma[D^0(t) \to K^+\pi^-] = e^{-\Gamma t}\,|A_{K^+\pi^-}|^2 \left[R + \sqrt{R}R_m\,(y'\cos\phi - x'\sin\phi)\,\Gamma t + \frac{R_m^2}{4}\,(x^2+y^2)\,(\Gamma t)^2\right]$$

$$R_m^2 = \left|\frac{q}{p}\right|^2, \quad x' = x\cos\delta + y\sin\delta, \quad y' = y\cos\delta - x\sin\delta$$

LHCb: $x'^2 = (-0.9 \pm 1.3) \times 10^{-4}$, $y' = (7.2 \pm 2.4) \times 10^{-3}$

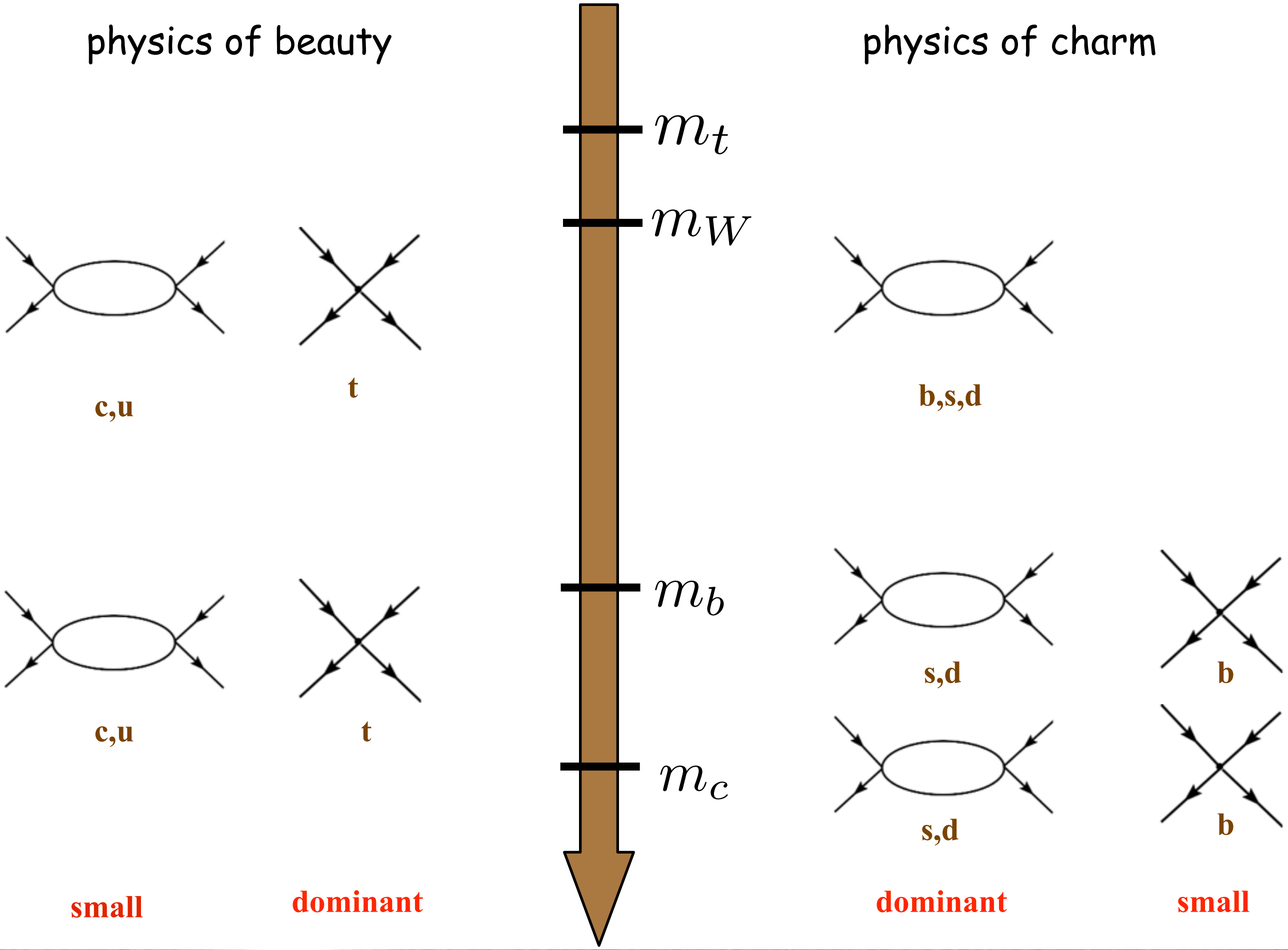
★ The expansion can be continued to see how well it converges for large t

$$\begin{aligned}\Gamma[D^0(t) \to K^+\pi^-]\,|A_{K\pi}|^{-2}e^{\Gamma t} = R \; &- \; \sqrt{R}R_m(x\sin(\delta+\phi) - y\cos(\delta+\phi))\,(\Gamma t) \\ &+ \frac{1}{4}\left((R_m - R)\,x^2 + (R + R_m)\,y^2\right)(\Gamma t)^2 \\ &+ \frac{1}{6}\sqrt{R}R_m\left(x^3\sin(\delta+\phi) + y^3\cos(\delta+\phi)\right)(\Gamma t)^3 \\ &- \frac{1}{48}R_m\left(x^4 - y^4\right)(\Gamma t)^4\end{aligned}$$

Δc = 2 example: mixing

★ Main goal of the exercise: understand physics at the most fundamental scale

★ It is important to understand relevant energy scales for the problem at hand



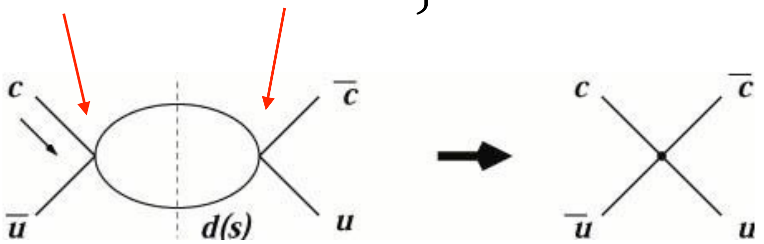
Mixing: short vs long distance

★ How can one tell that a process is dominated by long-distance or short-distance?

★ It is important to remember that the expansion parameter is $1/E_{released}$

$$y_D = \frac{1}{2M_D\Gamma_D} \mathrm{Im} \langle \overline{D^0} | \, i \int \mathrm{d}^4x \, T\left\{ \mathcal{H}_w^{|\Delta C|=1}(x) \, \mathcal{H}_w^{|\Delta C|=1}(0) \right\} | D^0 \rangle$$

OPE-leading contribution:



★ In the heavy-quark limit $m_c \to \infty$ we have $m_c \gg \sum m_{intermediate\ quarks}$, so $E_{released} \sim m_c$

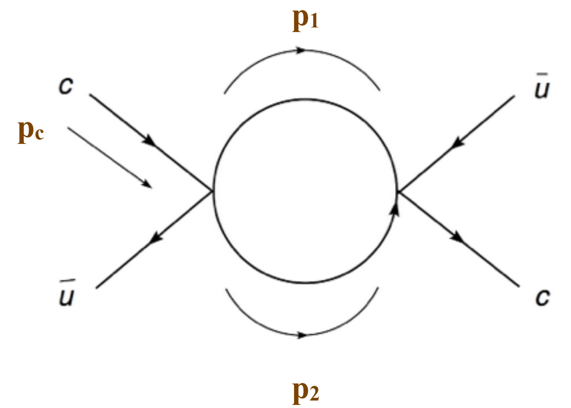
- the situation is similar to B-physics, where it is "short-distance" dominated
- one can consistently compute pQCD and 1/m corrections

★ But wait, m_c is NOT infinitely large! What happens for finite m_c???

- how is large momentum routed in the diagrams?
- are there important hadronization (threshold) effects?

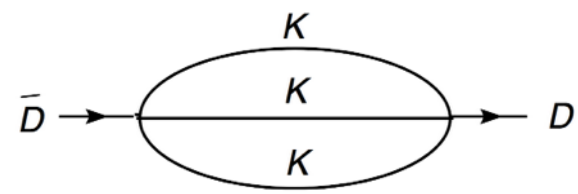
Threshold (and related) effects in OPE

★ How can one tell that a process is dominated by long-distance or short-distance?



★ Let's look how the momentum is routed in a leading-order diagram
- injected momentum is $p_c \sim m_c$, so
- thus, $p_1 \sim p_2 \sim m_c/2 \sim O(\Lambda_{QCD})$?

★ For a particular example of the lifetime difference, have hadronic intermediate states
- let's use an example of KKK intermediate state
- in this example, $E_{released} \sim m_D - 3\ m_K \sim O(\Lambda_{QCD})$



★ Similar threshold effects exist in B-mixing calculations
- but $m_b \gg \sum m_{intermediate\ quarks}$, so $E_{released} \sim m_b$ (almost) always
- quark-hadron duality takes care of the rest!

Maybe a better approach would be to work with hadronic DOF directly?

Generic restrictions on NP from $D\bar{D}$-mixing

★ Comparing to experimental value of x, obtain constraints on NP models...

- assume x is dominated by the New Physics model
- assume no accidental strong cancellations b/w SM and NP

Experiment	R_D ($\times10^{-3}$)	y' ($\times10^{-3}$)	x'^2 ($\times10^{-3}$)	Excl. No-Mix Significance	R_B ($\times10^{-3}$)
Belle (2006)	3.64 ± 0.17	0.6 ± 4.0	0.18 ± 0.22	2.0	3.77 ± 0.09
BaBar (2007)	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37	3.9	3.53 ± 0.09
LHCb	3.52 ± 0.15	7.2 ± 2.4	-0.09 ± 0.13	9.1	4.25 ± 0.04
CDF (9.6/fb)	3.51 ± 0.35	4.27 ± 4.30	0.08 ± 0.18	6.1	4.30 ± 0.06

M. Mattson, 2013

$$\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} z_i(\mu) Q_i'$$

★ ... which are

$$|z_1| \lesssim 5.7 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$
$$|z_2| \lesssim 1.6 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$
$$|z_3| \lesssim 5.8 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$
$$|z_4| \lesssim 5.6 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$
$$|z_5| \lesssim 1.6 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2.$$

New Physics is either at a very high scales

tree level: $\Lambda_{NP} \geq (4-10) \times 10^3$ TeV

loop level: $\Lambda_{NP} \geq (1-3) \times 10^2$ TeV

or has highly suppressed couplings to charm!

Gedalia, Grossman, Nir, Perez
Phys.Rev.D80, 055024, 2009

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
Phys. Rev. D76:095009, 2007

★ Constraints on particular NP models also available!

Transitions forbidden w/out CP-violation

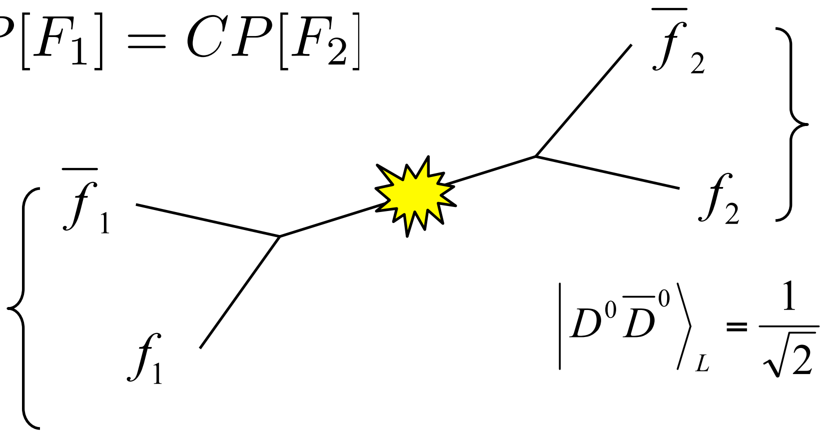
τ-charm factory

★ Recall that CP of the states in $D^0\overline{D^0} \rightarrow (F_1)(F_2)$ are anti-correlated at ψ(3770):

★ a simple signal of CP violation: $\psi(3770) \rightarrow D^0\overline{D^0} \rightarrow (CP_\pm)(CP_\pm)$

I. Bigi, A. Sanda; H. Yamamoto; Z.Z. Xing; D. Atwood, AAP

$$CP[F_1] = CP[F_2]$$



CP eigenstate F_2

CP eigenstate F_1

$$\left|D^0\overline{D}^0\right\rangle_L = \frac{1}{\sqrt{2}}\left[\left|D^0(k_1)\overline{D}^0(k_2)\right\rangle + (-1)^L\left|D^0(k_2)\overline{D}^0(k_1)\right\rangle\right]$$

$$\Gamma_{F_1F_2} = \frac{\Gamma_{F_1}\Gamma_{F_2}}{R_m^2}\left[\left(2+x^2+y^2\right)\left|\lambda_{F_1}-\lambda_{F_2}\right|^2 + \left(x^2+y^2\right)\left|1-\lambda_{F_1}\lambda_{F_2}\right|^2\right]$$

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

★ CP-violation in the **rate** → of the second order in CP-violating parameters.

★ Cleanest measurement of CP-violation!

AAP, Nucl. Phys. PS 142 (2005) 333
hep-ph/0409130