Theoretical review on charm mixing and decay and physics beyond SM

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Introduction

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

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

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

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

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

bi-local time-ordered product

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

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

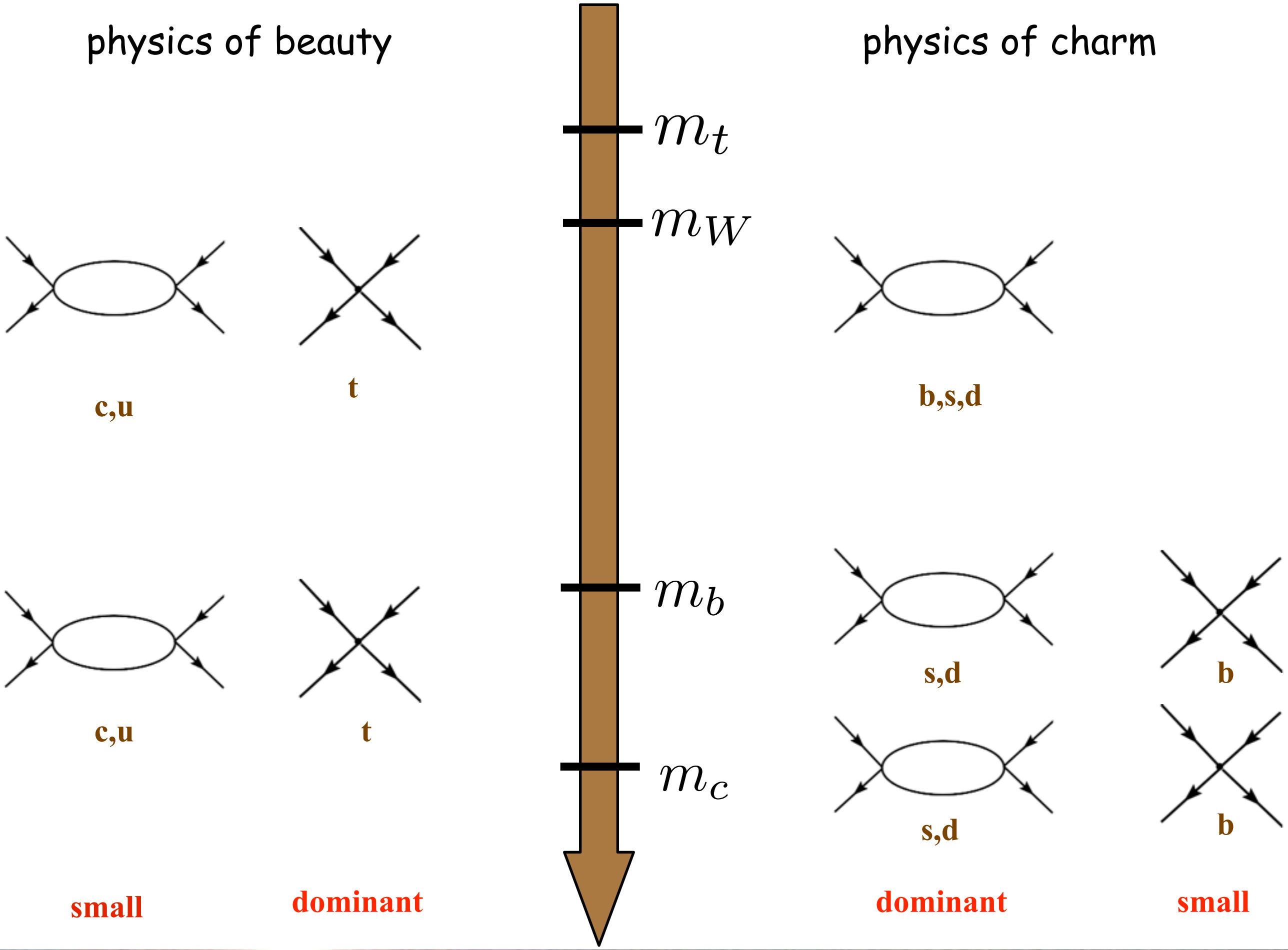
bi-local time-ordered product

★CP-violating phases can appear from subleading local SM or NP operators

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



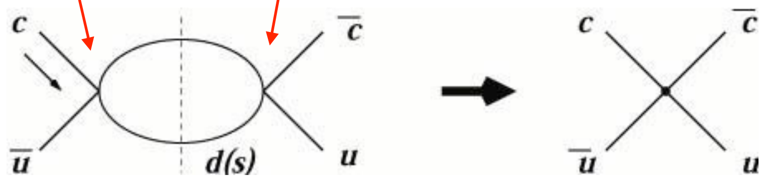
Mixing: short vs long distance

★ 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 $1/E_{released}$

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

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

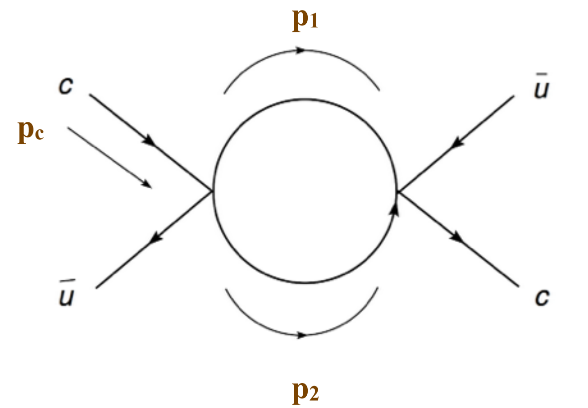
★ But wait, m_c is NOT infinitely large! What happens for finite m_c???

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

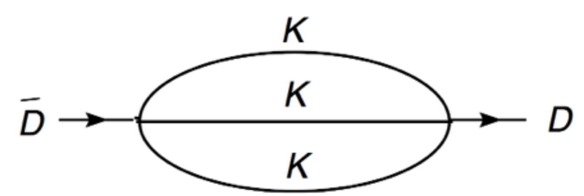
Threshold (and related) effects in OPE

★ 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, $p_1 \sim p_2 \sim m_c/2 \sim O(\Lambda_{QCD})$?



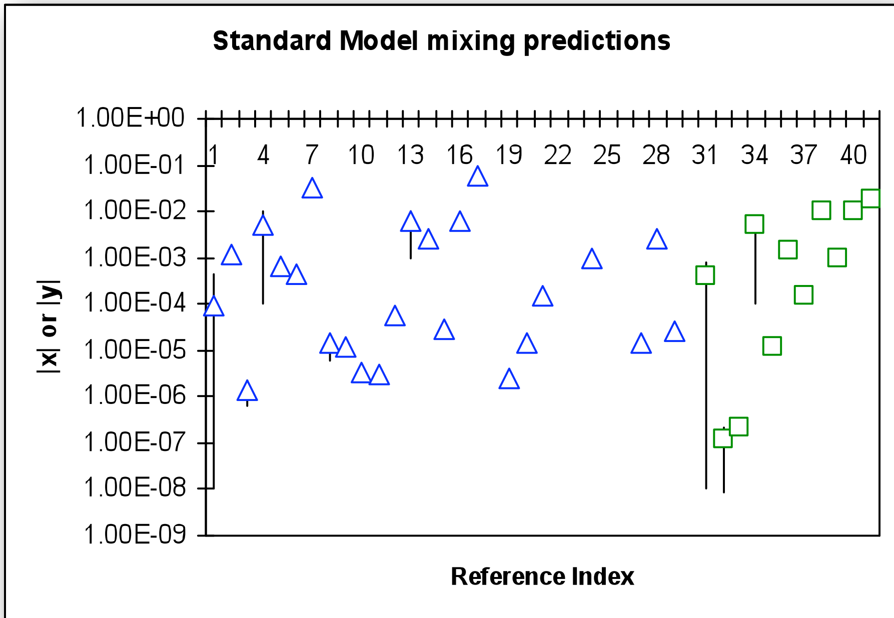
★ For a particular example of the lifetime difference, have hadronic intermediate states
- let's use an example of KKK intermediate state
- in this example, $E_{released} \sim m_D - 3\, m_K \sim O(\Lambda_{QCD})$

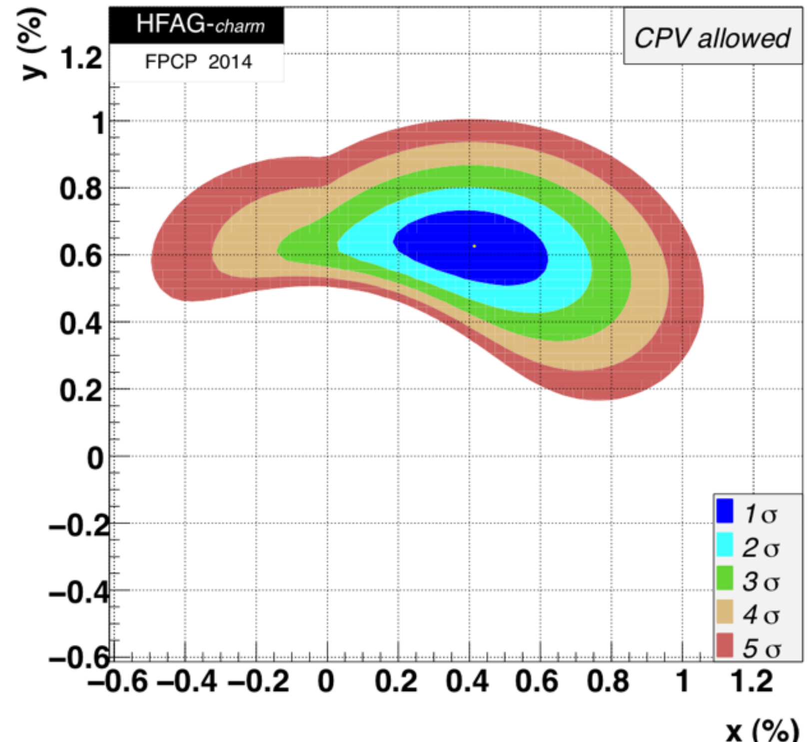


★ Similar threshold effects exist in B-mixing calculations
- but $m_b \gg \sum m_{intermediate\ quarks}$, so $E_{released} \sim m_b$ (almost) always
- quark-hadron duality takes care of the rest!

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

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 $|V_{cb}V_{ub}/V_{cs}V_{us}| \sim O(10^{-3})$

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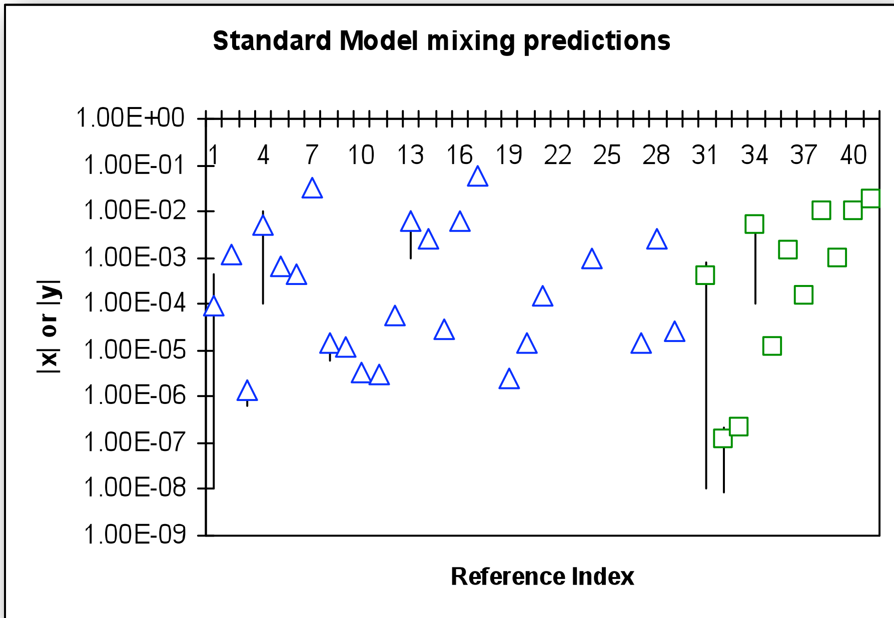

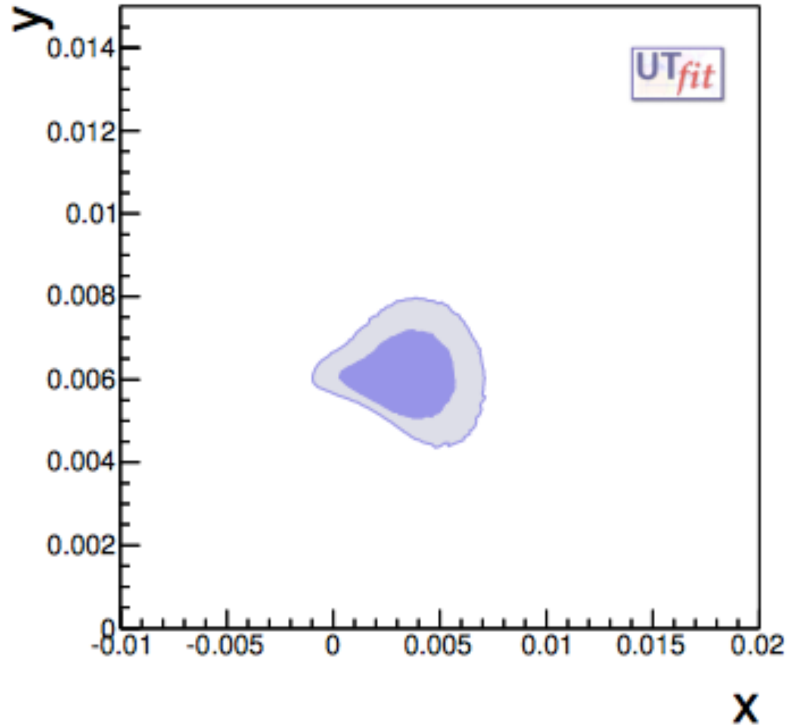

UTFit JHEP 1403 (2014) 123

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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

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

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

A bit on CP-violation

★ 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 ($\Delta c = 2$):

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

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

★ 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

- 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

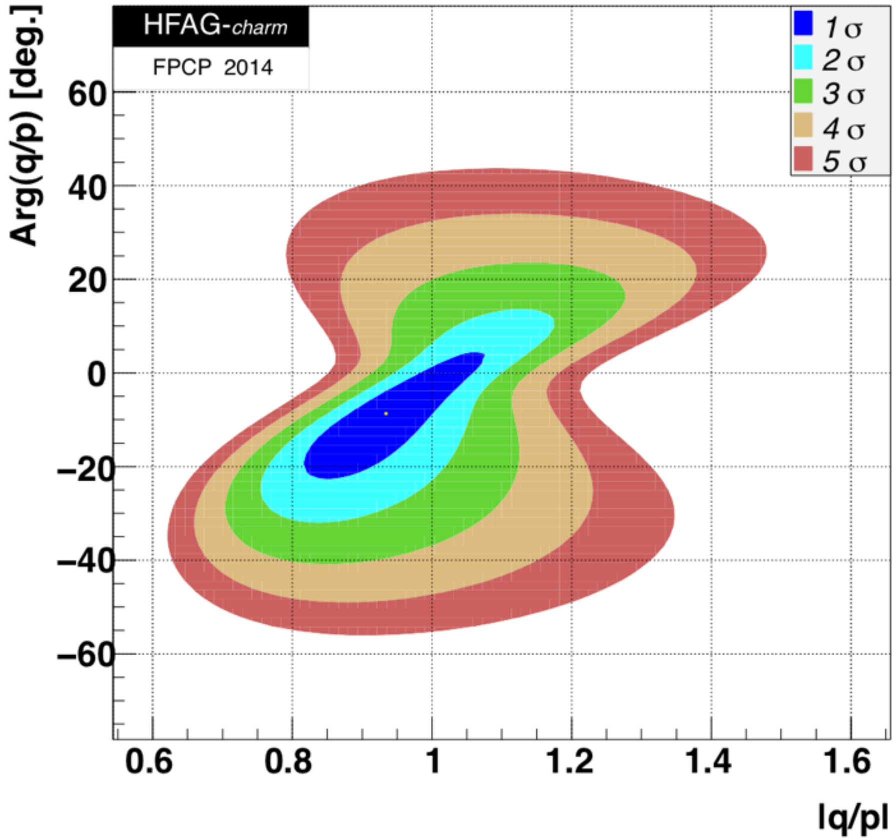
★ Relation; data from HFAG's compilation

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

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

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

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



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

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 $x_{12}^{\mathrm{NP}} \sin \phi_{12}^{\mathrm{NP}} \lesssim 0.0022$

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

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 have highly suppressed couplings to charm!

Gedalia, Grossman, Nir, Perez
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: $\lambda_{CP}^2 = R_m^2 e^{2i\phi}$

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

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

$$\phi_{12} = \phi_{12\,f}^M - \phi_{12\,f}^\Gamma$$

★ Can we put a Standard Model theoretical bound on $\phi_{12\,f}^M$ or $\phi_{12\,f}^\Gamma$?

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

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

★ 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

CP-violation II: direct

★ IDEA: consider the DIFFERENCE of decay rate asymmetries: D →ππ vs D → 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!

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

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

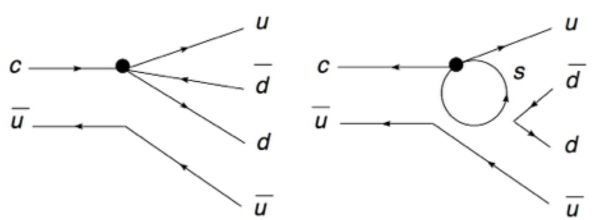
Is it Standard Model or New Physics??

★ 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.

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

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

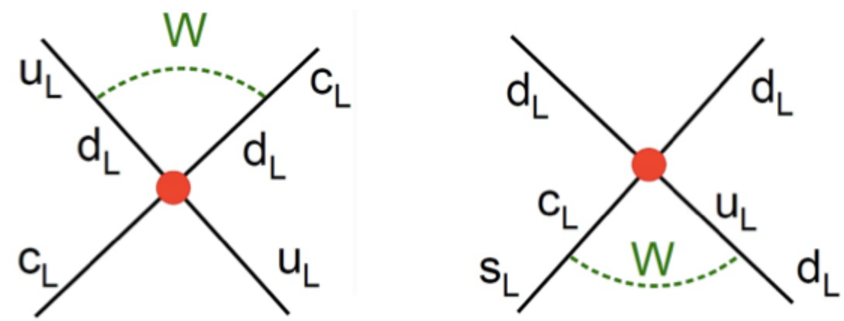
$$Q_2^q = (\bar{u}_\alpha q_\beta)_{V-A}\,(\bar{q}_\beta c_\alpha)_{V-A}$$

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

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

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

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



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?

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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.

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

Hansen, Sharpe
PRD86, 016007 (2012)

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

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

★ 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: transitions forbidden w/out CP-violation

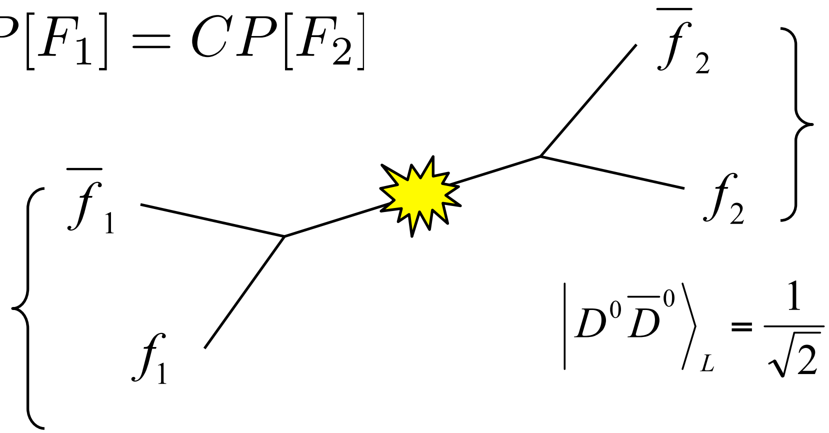
τ-charm factory

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

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

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 <u>**rate**</u> → of the second order in CP-violating parameters.

★ Cleanest measurement of CP-violation!

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

Future: Rare D(B)-decays with missing energy

➢ Let us discuss B and D-decays simultaneously: physics is similar

★ SM process: D → $\nu\nu$ and D → $\nu\nu\gamma$:

- for B-decays $J^{\mu}_{Qq} = \bar{q}_L \gamma^{\mu} b_L$
- for D-decays $J^{\mu}_{Qq} = \bar{u}_L \gamma^{\mu} c_L$

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2\theta_W} \sum_{l=e,\mu,\tau} \sum_k \lambda_k X^l(x_k)(J^{\mu}_{Qq}) \times (\bar{\nu}^l_L \gamma_\mu \nu^l_L),$$

Badin, AAP (2010)

★ For B(D) → $\nu\nu$ decays SM branching ratios are tiny

- SM decay is helicity suppressed

$$\mathcal{B}(B_s \to \nu\bar{\nu}) = \frac{G_F^2 \alpha^2 f_B^2 M_B^3}{16\pi^3 \sin^4\theta_W \Gamma_{B_s}} |V_{tb} V^*_{ts}|^2 X(x_t)^2 x_\nu^2$$

- NP: other ways of flipping helicity?
- add a third particle to the final state?

Decay	Branching ratio
$B_s \to \nu\bar{\nu}$	3.07×10^{-24}
$B_d \to \nu\bar{\nu}$	1.24×10^{-25}
$D^0 \to \nu\bar{\nu}$	1.1×10^{-30}

What would happen if a photon is added to the final state?

Rare D(B)-decays with missing energy

★ For B(D) $\to \nu\nu\gamma$ decays SM branching ratios are still tiny

- need form-factors to describe the transition

$$\langle\gamma(k)|\bar{b}\gamma_\mu q|B_q(k+q)\rangle = e\epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}q^\rho k^\sigma \frac{f_V^B(q^2)}{M_{B_q}}$$

$$\langle\gamma(k)|\bar{b}\gamma_\mu\gamma_5 q|B_q(k+q)\rangle = -ie[\epsilon_\mu^*(kq) - (\epsilon^* q)k_\mu] \times \frac{f_A^B(q^2)}{M_{B_q}},$$

$$\langle\gamma(k)|\bar{b}\sigma_{\mu\nu} q|B_q(k+q)\rangle = \frac{e}{M_{B_q}^2}\epsilon_{\mu\nu\lambda\sigma}[G\epsilon^{*\lambda}k^\sigma + H\epsilon^{*\lambda}q^\sigma + N(\epsilon^* q)q^\lambda k^\sigma]$$

Decay	Branching ratio
$B_s \to \nu\bar{\nu}\gamma$	3.68×10^{-8}
$B_d \to \nu\bar{\nu}\gamma$	1.96×10^{-9}
$D^0 \to \nu\bar{\nu}\gamma$	3.96×10^{-14}

Can calculate photon energy distributions as well.

Badin, AAP (2010)

- helicity suppression is lifted

$$A(B_q \to \nu\bar{\nu}\gamma) = \frac{2eC_1^{\mathrm{SM}}(x_t)}{M_{B_q}}[\epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}q^\rho k^\sigma f_V^B(q^2) + i[\epsilon_\mu^*(kq) - (\epsilon^* q)k_\mu]f_A^B(q^2)]\bar{\nu}_L\gamma^\mu\nu_L,$$

★ BUT: missing energy does not always mean neutrinos

- nice constraints on light Dark Matter properties !!!

Rare D(B)-decays: scalar DM

➢ Let us discuss B and D-decays simultaneously: physics is similar

Badin, AAP (2010)

★ Generic interaction Lagrangian: $\mathcal{H}_{eff} = \sum_i \frac{2C_i^{(s)}}{\Lambda^2} O_i$

- respective neutral currents for B-and D-decays

$$O_1 = m_Q \left(J_{Qq}\right)_{RL} \ (\chi_0^* \chi_0)$$
$$O_2 = m_Q \left(J_{Qq}\right)_{LR} \ (\chi_0^* \chi_0)$$
$$O_3 = \left(J_{Qq}^{\mu}\right)_{LL} \ \left(\chi_0^* \overleftrightarrow{\partial}_{\mu} \chi_0\right)$$
$$O_4 = \left(J_{Qq}^{\mu}\right)_{RR} \ \left(\chi_0^* \overleftrightarrow{\partial}_{\mu} \chi_0\right)$$

★ Scalar DM does not exhibit helicity suppression

- B(D) → E_{mis} is more powerful than B(D) → $E_{mis}\,\gamma$

$$\mathcal{B}(B_q \to \chi_0 \chi_0) = \frac{(C_1^{(s)} - C_2^{(s)})^2}{4\pi M_{B_q} \Gamma_{B_q}} \left(\frac{f_{B_q} M_{B_q}^2 m_b}{\Lambda^2 (m_b + m_q)}\right)^2 \times \sqrt{1 - 4x_\chi^2},$$

$$\mathcal{B}(B_q \to \chi_0^* \chi_0 \gamma) = \frac{f_{B_q}^2 \alpha C_3^{(s)} C_4^{(s)} M_{B_q}^5}{6\Lambda^4 \Gamma_{B_q}} \left(\frac{F_{B_q}}{4\pi}\right)^2 \times \left(\frac{1}{6}\sqrt{1 - 4x_\chi^2}(1 - 16x_\chi^2 - 12x_\chi^4) - 12x_\chi^4 \log \frac{2x_\chi}{1 + \sqrt{1 - 4x_\chi^2}}\right).$$

$$\left(\frac{C_1^{(s)} - C_2^{(s)}}{\Lambda^2}\right)^2 \leq 2.07 \times 10^{-16} \text{ GeV}^{-4} \quad \text{for } m_\chi = 0.1 \times M_{B_d},$$

$$\frac{C_3^{(s)}}{\Lambda^2} \frac{C_4^{(s)}}{\Lambda^2} \leq 1.55 \times 10^{-12} \text{ GeV}^{-4} \quad \text{for } m = 0,$$

$$\frac{C_3^{(s)}}{\Lambda^2} \frac{C_4^{(s)}}{\Lambda^2} \leq 7.44 \times 10^{-11} \text{ GeV}^{-4} \quad \text{for } m = 0.4 \times M_{B_d}$$

These general bounds translate into constraints onto constraints for particular models

Example of a particular model of scalar DM

★ Several different models of light scalar DM
- simplest: singlet scalar DM
- more sophisticated - less restrictive

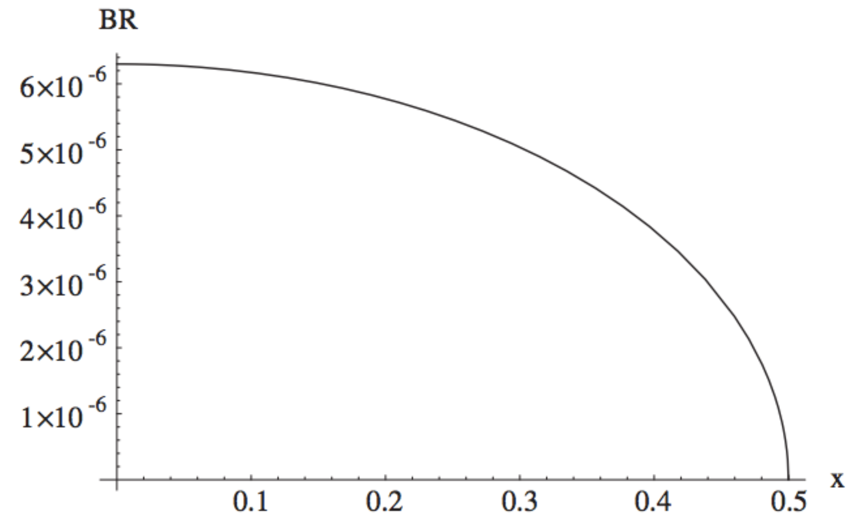
$$-\mathcal{L}_S = \frac{\lambda_S}{4}S^4 + \frac{m_0^2}{2}S^2 + \lambda S^2 H^\dagger H$$
$$= \frac{\lambda_S}{4}S^4 + \frac{1}{2}(m_0^2 + \lambda v_{\rm EW}^2)S^2 + \lambda v_{\rm EW} S^2 h$$
$$+ \frac{\lambda}{2}S^2 h^2,$$

★ B(D) decays rate in this model

$$\mathcal{B}(B_q \to SS) = \left[\frac{3g_w^2 V_{tb}V_{tq}^* x_t m_b}{128\pi^2}\right]^2 \frac{\sqrt{1-4x_S^2}}{16\pi M_B \Gamma_{B_q}}\left(\frac{\lambda^2}{M_H^4}\right) \times \left(\frac{f_{B_q} M_{B_q}^2}{m_b + m_q}\right)^2,$$

- fix λ from relic density

$$\sigma_{\rm ann} v_{\rm rel} = \frac{8 v_{\rm EW}^2 \lambda^2}{M_H^2} \times \lim_{m_{h^*}\to 2m_S} \frac{\Gamma_{h^* X}}{m_h^*}$$



These results are complimentary to constraints from quarkonium decays with missing energy

Rare D(B)-decays: fermionic DM

★ Generic interaction Lagrangian: $\mathcal{H}_{eff} = \sum_i \frac{4C_i}{\Lambda^2} O_i$

- respective neutral currents for B-and D-decays

$$O_1 = \left(J^\mu_{Qq}\right)_{LL} \left(\bar{\chi}_{1/2L}\gamma_\mu\chi_{1/2L}\right)$$
$$O_2 = \left(J^\mu_{Qq}\right)_{LL} \left(\bar{\chi}_{1/2R}\gamma_\mu\chi_{1/2R}\right)$$
$$O_3 = O_{1(L\leftrightarrow R)}, \quad O_4 = O_{2(L\leftrightarrow R)}$$
$$O_5 = \left(J_{Qq}\right)_{LR} \left(\bar{\chi}_{1/2L}\ \chi_{1/2R}\right)$$
$$O_6 = \left(J_{Qq}\right)_{LR} \left(\bar{\chi}_{1/2R}\ \chi_{1/2L}\right)$$
$$O_7 = O_{5(L\leftrightarrow R)}, \quad O_8 = O_{6(L\leftrightarrow R)}$$
$$+ \ \text{tensor operators}$$

Badin, AAP

★ Scalar DM does exhibit helicity suppression

- B(D) $\rightarrow$ E$_{mis}$ maybe less powerful than B(D) $\rightarrow$ E$_{mis}\,\gamma$
- … but it really depends on the DM mass!

$$\mathcal{B}(B_q \to \bar{\chi}_{1/2}\chi_{1/2}) = \frac{f_{B_q}^2 M_{B_q}^3}{16\pi\Gamma_{B_q}\Lambda^2}\sqrt{1-4x_\chi^2}$$
$$\times\left[C_{57}C_{68}\frac{4M_{B_q}^2 x_\chi^2}{(m_b+m_q)^2} - (C_{57}^2 + C_{68}^2)\right.$$
$$\times\frac{M_{B_q}^2(2x_\chi^2-1)}{(m_b+m_q)^2} - 2\tilde{C}_{1-8}\frac{x_\chi M_{B_q}}{m_b+m_q}$$
$$\left. + 2(C_{13}+C_{24})^2 x_\chi^2\right],$$

Lots of operators — less so in particular models

Rare D(B)-decays: fermionic DM

★ Constraints from B decays are the best at the moment

TABLE I. Constraints (upper limits) on the Wilson coefficients of operators of Eq. (43) from the $B_q \to \chi_{1/2}\bar{\chi}_{1/2}$ transition. Note that operators Q_9–Q_{12} give no contribution to this decay.

x_χ	C_1/Λ^2, GeV^{-2}	C_2/Λ^2, GeV^{-2}	C_3/Λ^2, GeV^{-2}	C_4/Λ^2, GeV^{-2}	C_5/Λ^2, GeV^{-2}	C_6/Λ^2, GeV^{-2}	C_7/Λ^2, GeV^{-2}	C_8/Λ^2, GeV^{-2}
0	...	...	...	...	2.3×10^{-8}	2.3×10^{-8}	2.3×10^{-8}	2.3×10^{-8}
0.1	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	2.3×10^{-8}	2.3×10^{-8}	2.3×10^{-8}	2.3×10^{-8}
0.2	9.7×10^{-8}	9.7×10^{-8}	9.7×10^{-8}	9.7×10^{-8}	2.5×10^{-8}	2.5×10^{-8}	2.5×10^{-8}	2.5×10^{-8}
0.3	6.9×10^{-8}	6.9×10^{-8}	6.9×10^{-8}	6.9×10^{-8}	2.8×10^{-8}	2.8×10^{-8}	2.8×10^{-8}	2.8×10^{-8}
0.4	6.0×10^{-8}	6.0×10^{-8}	6.0×10^{-8}	6.0×10^{-8}	3.6×10^{-8}	3.6×10^{-8}	3.6×10^{-8}	3.6×10^{-8}

★ … the same is true for the radiative decays with missing energy

TABLE II. Constraints (upper limits) on the Wilson coefficients of operators of Eq. (43) from the $B_q \to \chi_{1/2}\bar{\chi}_{1/2}\gamma$ transition. Note that operators Q_5–Q_8 give no contribution to this decay.

x_χ	C_1/Λ^2, GeV^{-2}	C_2/Λ^2, GeV^{-2}	C_3/Λ^2, GeV^{-2}	C_4/Λ^2, GeV^{-2}
0	6.3×10^{-7}	6.3×10^{-7}	6.3×10^{-7}	6.3×10^{-7}
0.1	7.0×10^{-7}	7.0×10^{-7}	7.0×10^{-7}	7.0×10^{-7}
0.2	9.2×10^{-7}	9.2×10^{-7}	9.2×10^{-7}	9.2×10^{-7}
0.3	1.5×10^{-6}	1.5×10^{-6}	1.5×10^{-6}	1.5×10^{-6}
0.4	3.4×10^{-6}	3.4×10^{-6}	3.4×10^{-6}	3.4×10^{-6}

These general bounds translate into constraints onto constraints for particular models

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}!
- Decays to states with missing energy probe light DM
- 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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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

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

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

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

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