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short-distance D^0–$\bar{D}^0$ mixing

5^{th} international workshop on charm physics

Honolulu, Hawaii – May 16, 2012

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Outline

▷ **work with Alex Lenz & Ulrich Nierste**

- Neutral meson mixing: an introduction
- OPE of the $\Delta C = 2$ Hamiltonian
- SU(3) breaking from the sea background
- Conclusions

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CPV in D^0 mixing

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Mixing & CPV in charm is a unique NP search channel probed at a precision level by LHCb.

- severe bounds on the effective scale of various $\Delta C = 2$ operators: $\Lambda \gtrsim 10^3$ TeV
  - ▷ Isidori, Nir, & Perez ('10)
- it is possible to probe up-type FCNC (maybe NP is aligned in the down-sector)
  - ▷ Gedalia, Grossman, Nir, & Perez ('09)
- we have experimental evidence for CPV in $D^0 \to K^- K^+, \pi^- \pi^+$
  - ▷ LHCb-CONF-2011-061 & CERN-PH-EP-2011-208 (LHCb); CDF Note 10784 (CDF)
- SM charm physics dominated by two generations $\rightsquigarrow$ CPV tiny in mixing & tree-decay.
  - ▷ e.g. Falk, Grossman, Ligeti, Nir, & Petrov ('04); Alex Kagan @ FPCP 2011

> CPV in mixing enters at $\mathcal{O}\left(\frac{V_{cb}^* V_{ub}}{V_{cs}^* V_{us}}\right) \simeq 10^{-3}$.
>
> It's crucial for any NP search to assess the SM CPV background.

I will argue that it may be possble to accommodate CPV of 1 per mille in mixing.

neutral meson oscillations

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left(\hat{M} - \frac{i}{2}\hat{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

neutral meson oscillations

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3 parameters for mixing & CPV:

$$|M_{12}|,\ |\Gamma_{12}|,\ \phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

$|\cos\phi| \simeq 1$

$\Delta\Gamma / \Delta M = \mathcal{O}(1)$

▷ HFAG

translate into 3 mixing-related observables...

- mass and decay width differences

$$\Delta M = M_H - M_L, \quad \Delta\Gamma = \Gamma_L - \Gamma_H$$

$$\Delta M = 2|M_{12}|$$

$$\Delta\Gamma = 2|\Gamma_{12}|\ \mathrm{sgn}\cos\phi$$

- flavour-specific CP asymmetries

$$a_f = \frac{\Gamma\left(\bar{D}(t) \to f\right) - \Gamma\left(D(t) \to \bar{f}\right)}{\Gamma\left(\bar{D}(t) \to f\right) + \Gamma\left(D(t) \to \bar{f}\right)}$$

$$a_f = \left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\phi \ll 1$$

CPV in mixing is small!

recent experimental status

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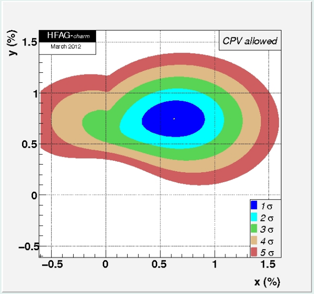
- current HFAG average
  - ▷ BaBar, Belle, CDF, CLEO

$$x = 0.63^{+0.19}_{-0.20}\,\%$$
$$y = (0.75 \pm 0.12)\,\%$$
$$|q/p| = 0.88^{+0.18}_{-0.16}$$
$$\phi = -10.1^{+9.5}_{-8.9}{}^{\circ}$$



- these results imply. . .
  - ▷ Grossman, Nir, & Perez ('09)

1. mass & width splitting are at $\sim 1\%$.
2. CPV in mixing is small.

exclusive approach

▷ Wolfenstein ('85); Donoghue & al. ('86); Buccella, Lusignoli, & Pugliese ('96); Golowich & Petrov ('98)

Sum over final states common to D^0 & $\bar{D}^0$ decays...

$$y = \frac{1}{\Gamma} \sum_f \rho_f \ \mathrm{Re} \left\langle \bar{D}^0 \middle| \mathcal{H}_\mathrm{w} \middle| f \right\rangle \left\langle f \middle| \mathcal{H}_\mathrm{w} \middle| D^0 \right\rangle$$

- needs a multitude of exclusive decay amplitudes & strong phases
- assume SU(3) and CP invariance in the matrix elements
  and estimate the contribution from SU(3) breaking in phase space – provided
  ▷ Falk, Grossman, Ligeti and Petrov ('02); Falk, Grossman, Ligeti, Nir, & Petrov ('04)
  - phase space does not interfere with matrix elements
  - SU(3) multiplets do not interfere
- SU(3)-breaking from nearby pseudoscalar resonances
  ▷ Golowich ('81); Golowich & Petrov ('98); Gronau ('99); Falk, Nir, & Petrov ('99); Falk & al. ('02)

...usually $x, y = \mathcal{O}(1\%)$ is considered as natural

inclusive approach

▷ **Georgi ('92); Ohl, Ricciardi, & Simmons ('93); Bigi & Uraltsev ('01); Golowich, Pakvasa, & Petrov ('07)**

The **Heavy Quark Expansion** expands the $\Delta C = 2$ Hamiltonian into a series of local operators of increasing dimension (expansion in Λ / m_q):

$$\hat{M} - \frac{\mathrm{i}}{2}\hat{\Gamma} = -\frac{\mathrm{i}}{4 M_D} \int \mathrm{d}^4 x \, \langle \mathrm{T}\, \mathcal{H}_\mathrm{w}(x)\, \mathcal{H}_\mathrm{w}(0) \rangle$$

$$= \sum_{\dim n = 0}^{\infty} \left(\frac{\Lambda}{m_q} \right)^n \mathbf{G}_n \, \langle \mathbf{Q}_n \rangle$$

This assumes quark hadron duality to hold.

this approach is a story of success in B physics, yet it's not clear whether $\Lambda/m \ll 1$ actually works in charm

assessing the OPE picture

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- first measurement of $\Delta\Gamma(B_s)$ from LHCb at Moriond 2012

$$\frac{\Delta\Gamma\left(B_s\right)_{\text{exp}}}{\Delta\Gamma\left(B_s\right)_{\text{SM}}} = \frac{0.100 \pm 0.013}{0.087 \pm 0.021} = 1.15 \pm 0.32$$

▷ LHCb & TeVatron combined 2012; Lenz & Nierste, 1102.4274 (2011)

$\Gamma_{12}\left(B_s\right)$ is believed to be most sensitive to violations of quark hadron duality. The HQE succeeds work within 30% accuracy.

- inclusive rates should be less sensitive to duality violation and agree amazingly well

$$\frac{\tau\left(B_s\right)_{\text{exp}}}{\tau\left(B_d\right)} = 1.001 \pm 0.014, \quad \frac{\tau\left(B_s\right)_{\text{SM}}}{\tau\left(B_d\right)} = 0.996 \ldots 1.000$$

▷ LHCb & TeVatron combined 2012; Lenz & Nierste, 1102.4274 (2011)

energy releases in dominant decays are not quite different for the D system

$$m_{B_s} - 2m_{D_s} \simeq 1.428\ \text{GeV}$$
$$m_D - 2m_K \simeq 0.9\ \text{GeV}$$
$$m_D - 2m_\pi \simeq 1.6\ \text{GeV}$$

Outline

heavy quark expansion

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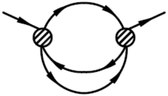
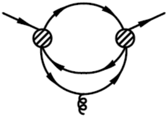
$$\mathcal{H} = \mathcal{H}_0 + \left(\frac{\Lambda}{m_c}\right)^2 \mathcal{H}_2 + \left(\frac{\Lambda}{m_c}\right)^3 \mathcal{H}_3 + \left(\frac{\Lambda}{m_c}\right)^4 \mathcal{H}_4 + \dots$$

▷ **Beneke, Buchalla, & Dunietz ('96); Beneke, Buchalla, Greub, Lenz, & Nierste ('99); Ciuchini, Franco, Lubicz, Mescia, & Tarantino ('03); Beneke, Buchalla, Lenz, & Nierste ('03)**



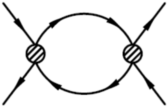
- $D = 3$: $\mathcal{H}_0$ – spectator model quark decay

  c-hadron mean lifetime



- $D = 5$: $\mathcal{H}_2$ – corrections from kinetic & chromomagnetic operator

  $\bar{q}\, D^2\, q$ **and** $\bar{q}\,(G\sigma)\, q$



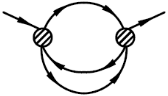
- $D = 6$: $\mathcal{H}_3$ – weak annihilation & Pauli interference

  mixing and lifetime differences between c-hadrons

heavy quark expansion

$$\mathcal{H}_{12} = \mathcal{H}_0 + \left(\frac{\Lambda}{m_c}\right)^2 \mathcal{H}_2 + \left(\frac{\Lambda}{m_c}\right)^3 \mathcal{H}_3 + \left(\frac{\Lambda}{m_c}\right)^4 \mathcal{H}_4 + \ldots$$

▷ **Beneke, Buchalla, & Dunietz ('96); Beneke, Buchalla, Greub, Lenz, & Nierste ('99); Ciuchini, Franco, Lubicz, Mescia, & Tarantino ('03); Beneke, Buchalla, Lenz, & Nierste ('03)**



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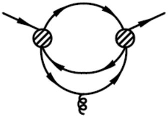

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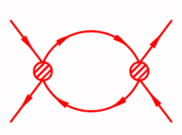
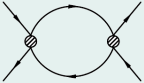


- $D = 6$: $\mathcal{H}_3$ – weak annihilation & Pauli interference

  mixing and lifetime differences between c-hadrons

SU(3) symmetry and GIM mechanism

$\Gamma_{12} = \mathrm{Im}\Big($  $\Big)$

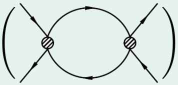
Γ_{12} is the absorptive part of the loop. — compare D^0 and B^0 mixing:

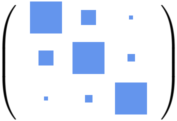
$$B^0_{d,s}: \quad \Gamma_{12} = -\left(\lambda_c^2 \Gamma_{12}^{cc} + 2\lambda_c\lambda_u \Gamma_{12}^{uc} + \lambda_u^2 \Gamma_{12}^{uu}\right)$$

$$D^0: \quad \Gamma_{12} = -\left(\lambda_s^2 \Gamma_{12}^{ss} + 2\lambda_s\lambda_d \Gamma_{12}^{ds} + \lambda_d^2 \Gamma_{12}^{dd}\right)$$

using unitarity $\lambda_d + \lambda_s + \lambda_b = 0 \ldots$

SU(3) symmetry and GIM mechanism

$\Gamma_{12} = \mathrm{Im}$ 

CKM couplings induce a hierachy: $V_{\mathrm{CKM}} =$ 

the individual terms scale with flavour symmetry breaking,
interference within SU(3) multipletts (D^0) instead of SU(4) multiplets (B^0)

$$\Gamma_{12}(B^0) = -\lambda_c^2 \left(\Gamma_{12}^{cc} - 2\Gamma_{12}^{uc} + \Gamma_{12}^{uu}\right) + 2\lambda_c\lambda_t \left(\Gamma_{12}^{uc} - \Gamma_{12}^{uu}\right) - \lambda_t^2 \, \Gamma_{12}^{uu}$$

$$\Gamma_{12}(D^0) = -\lambda_s^2 \left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{ds} + \Gamma_{12}^{dd}\right) + 2\lambda_s\lambda_b \left(\Gamma_{12}^{ds} - \Gamma_{12}^{dd}\right) - \lambda_b^2 \, \Gamma_{12}^{dd}$$

SU(3) symmetry and GIM mechanism

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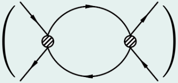
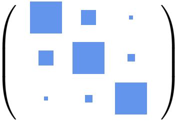
$\Gamma_{12} = \mathrm{Im}$ 

CKM couplings induce a hierachy: $V_{\mathrm{CKM}} =$ 

the individual terms scale with flavour symmetry breaking,
interference within SU(3) multipletts (D^0) instead of SU(4) multiplets (B^0)

$$\Gamma_{12}(B^0) \sim -\lambda^6 \times m_c^4/m_b^4 + \lambda^6 \times m_c^2/m_b^2 - \lambda^6 \times 1$$

$$\Gamma_{12}(D^0) \sim -\lambda^2 \times m_s^4/m_c^4 + \lambda^6 \times m_s^2/m_c^2 - \lambda^{10} \times 1$$

GIM → D mesons mix slowly due to CKM hierarchy and residual SU(3) symmetry

width splitting

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$$\Gamma_{12}(D^0) = -\lambda_s^2 \underbrace{\left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{sd} + \Gamma_{12}^{dd}\right)}_{1.15\, m_s^4/m_c^4 \,-\, 59.7\, m_s^6/m_c^6} + 2\lambda_s\lambda_b \underbrace{\left(\Gamma_{12}^{sd} - \Gamma_{12}^{dd}\right)}_{-2.75\, m_s^2/m_c^2} - \lambda_b^2 \underbrace{\Gamma_{12}^{dd}}_{1.96}$$

$$\Gamma_{12}/(10^{-6}\,\mathrm{ps}^{-1}) = 1.40 + 1.71\, e^{-0.6\,\pi i} + 0.04\, e^{-0.3\,\pi i} = -2.0 + 1.6\, i$$

$$|y| \equiv |\Gamma_{12}| \cdot \tau_D \simeq 10^{-6}$$

▷ **MB, Lenz, Riedl, & Rohrwild ('10)**

- people liked to set $\lambda_b/\lambda_s \simeq 0$ from the beginning. Γ_{12} will then be real, just as λ_s.
- actually, the $\sim \lambda_b\lambda_s \times m_s^2/m_c^2$ term has one order more SU(3) breaking and turns out to be competitive with the $\sim \lambda_s^2 \times m_s^4/m_c^4$ one.

We see there's actually an order one weak phase in the width matrix.

In magnitude (of course), the results still fails by a factor of 10^3.

What is the dominant contribution to $\Delta\Gamma$?

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beyond HQE

- heavy quark methods unreliable
  - Λ/m_c not sufficiently small
  - QCD large at 1 GeV

  ▷ MB, Lenz, Riedl, & Rohrwild ('10)

  max. 50% from NLO and 1/m
- violation of quark-hadron duality due to long-distance dynamics

  That's not captured by OPE!

within HQE

- new sources of SU(3) breaking enhance

  $$\Gamma_{12}^{ss} - 2\Gamma_{12}^{sd} + \Gamma_{12}^{dd}$$

  ▷ MB, Lenz, & Nierste

  Higher-dimension operators can do that.
- NP modifying CKM unitarity

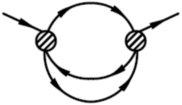
  ▷ MB, Lenz, Riedl, & Rohrwild ('09)

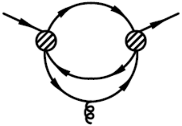
  e.g. with a fourth family

NP with right-handed weak currents

▷ Golowich, Hewett, Pakvasa, & Petrov ('07)

meson lifetimes in the OPE





- Inclusive rates are much less affected by GIM or duality violation. This may be a good testing ground for the OPE.
- deviation from spectator model

$$\Gamma = \Gamma_0(c)\left(1+\delta\right)$$

- neglect phase space differece in the charged SU(3) multiplet, $\Pi_{fs}(D^+) = \Pi_{fs}(D_s^+)$

$$\frac{\tau\left(D^+\right)}{\tau\left(D^0\right)} \equiv \frac{\Gamma_0(c)}{\Gamma_0(c)}\frac{1+\delta\left(D^0\right)}{1+\delta\left(D^+\right)} = \frac{1+\delta\left(D^0\right)}{1+\delta\left(D^+\right)} \simeq 2.5$$

$$\frac{\tau\left(D_s^+\right)}{\tau\left(D^0\right)} \equiv \frac{\Gamma_0(c)}{\Gamma_0(c)}\frac{1+\delta\left(D^0\right)}{1+\delta\left(D_s^+\right)} = \frac{1+\delta\left(D^0\right)}{1+\left|V_{us}/V_{ud}\right|^2\delta\left(D^+\right)} \simeq 1.2$$

$$\delta\left(D^0\right) = +17\%$$

$$\delta\left(D^+\right) = -53\%$$

hadronic uncertainties cancel!

This is only a first guess. We're working on a serious calculation.

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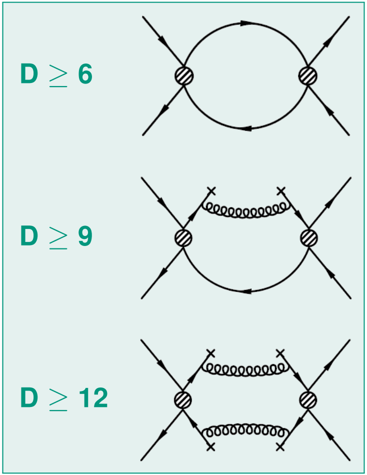
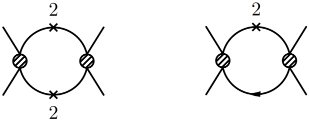
the meson's soft QCD background



interference within SU(3) multiplets:

$$-\lambda^2 \underbrace{\left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{ds} + \Gamma_{12}^{dd}\right)}_{(m_s/m_c)^4} + \lambda^6 \underbrace{\left(\Gamma_{12}^{ds} - \Gamma_{12}^{dd}\right)}_{(m_s/m_c)^2} - \lambda^{10}\, \Gamma_{12}^{dd}$$



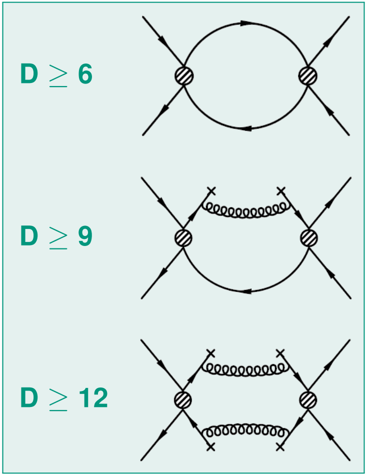
If an internal momentum is $\lesssim \Lambda_{\mathrm{QCD}}$, the intermediate state couples to the meson's soft QCD substructure.

SU(3) breaking arises from the hadron state: albeit subleading in $1/m_c$, the amplitude carries less powers of m_s and can actually dominate the OPE.

▷ **Georgi ('92); Ohl, Ricciardi, & Simmons ('93); Bigi & Uraltsev ('01)**

→ cutting one internal line may lift one order of SU(3) suppression

hadronic matrix elements at $D = 9$



SU(3) breaking from non-perturbative soft QCD dynamics, enters the OPE through hadronic matrix elements of 6-quark operators

factorization limit ($\sim 1/N_c$)

▷ **MB & Alex Lenz**

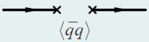
model the mesons's sea quark content with the vacuum condensate, neglecting higher excitations in the meson state

the quark field operators from the intermediate state are taken to be saturated with vacuum

→ the matrix elements of the remaining 4-quark operators are known from the lattice

diquark condensate intermediate states

QCD vacuum condensation:

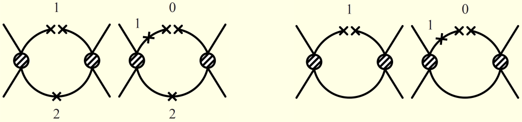


$$= \langle\, \underset{\sim}{0} \,|\, : q(x) \otimes \bar{q}(0) : \,|\, \underset{\sim}{0} \,\rangle = -\frac{\langle \bar{q}q \rangle}{4N_c} \times \mathbb{1}_c \left(\mathbb{1}_D - \frac{i\, m}{d} \not{x} \right)$$

SU(3) breaking expected from a single condensate insertion competes with $\times 4\pi\alpha_s \dfrac{\langle \bar{s}s \rangle}{m_c^3} \simeq 0.3$

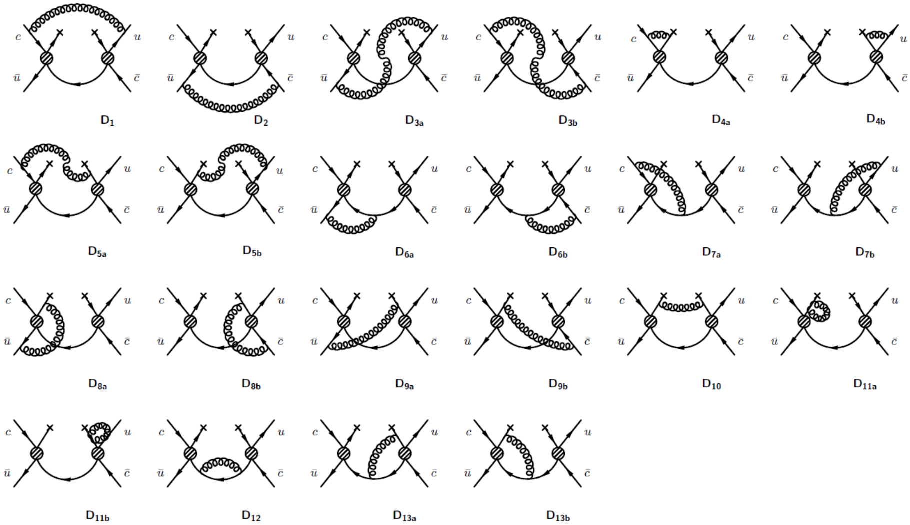
$$\delta\,\Gamma_{12} = -\lambda_s^2 \left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{ds} + \Gamma_{12}^{dd}\right) + 2\lambda_s\lambda_b \left(\Gamma_{12}^{ds} - \Gamma_{12}^{dd}\right) - \lambda_b^2\, \Gamma_{12}^{dd}$$

$\sim (m_s / m_c)^3$ $\quad\quad$ $\sim m_s / m_c$



- cutting one line, we have gained one power of m_s
- one factor m_s is intrinsic to the matrix element of the 6-quark operator

diquark condensate intermediate states



width splitting

- SU(3) cancellations softer in the condensate contribution

$$\Gamma_{12} = -\lambda_s^2 \underbrace{\left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{ds} + \Gamma_{12}^{dd}\right)}_{1.15\, m_s^4/m_c^4} + 2\lambda_s\lambda_b \underbrace{\left(\Gamma_{12}^{ds} - \Gamma_{12}^{dd}\right)}_{-2.75\, m_s^2/m_c^2} - \lambda_b^2 \underbrace{\Gamma_{12}^{dd}}_{1.96}$$

$$\delta\Gamma_{12} = -\lambda_s^2 \underbrace{\delta\left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{ds} + \Gamma_{12}^{dd}\right)}_{0.43\, m_s^3/m_c^3} + 2\lambda_s\lambda_b \underbrace{\delta\left(\Gamma_{12}^{ds} - \Gamma_{12}^{dd}\right)}_{0.19\, m_s/m_c} - \lambda_b^2 \underbrace{\delta\Gamma_{12}^{dd}}_{0}$$

$\times 13$ $\times 0.66$

- flavour symmetry breaking:

$\Gamma_{12}^{ss}/\text{ps}^{-1} = 1.908 + 0.036$ $(+1.9\%)$

$\Gamma_{12}^{sd}/\text{ps}^{-1} = 1.935 + 0.018$ $(+0.9\%)$

$\Gamma_{12}^{dd}/\text{ps}^{-1} = 1.962 + 0$

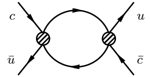
$$y = (0.86 + 7.3) \cdot 10^{-6}$$

$\times 8.5$

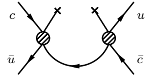
▷ MB, Lenz, & Nierste

→ additional SU(3) breaking induced from the soft QCD background

mass splitting and CPV

$$M_{12} = \mathrm{Re}\,\Big($$


$$\Big) = (0.2 + 6.9\,\mathrm{i}) \cdot 10^{-5}\mathrm{ps}^{-1}$$

$$\delta M_{12} = \mathrm{Re}\,\Big($$


$$\Big) = -(1.7 + 0.1\,\mathrm{i}) \cdot 10^{-5}\mathrm{ps}^{-1}$$

weak phase in the SD-Hamiltonian

$$\phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \simeq \mathbf{1.8}$$

Maybe there is some mechanism to break the remaining GIM interference.
(e.g. by cutting the second line, non-factorisable contributions, . . .)

If the effect is able to push x and y up to the observed values, then $\phi = 10^{-3}$ is within reach (this is pure speculation!)

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summary & outlook

- we investigated $SU(3)$ breaking effects at higher orders in the HQE
- assuming factorisation of sea quark operators, we find an $\mathcal{O}(10)$ enhancement in $\Delta\Gamma$ at operator dimension nine
- the standard argument for a small phase is not quite true, due to $SU(3)$ interference
- as regards CPV...

> We see an $\mathcal{O}(1)$ weak phase in the SD Hamiltonian.
>
> If HQE works and it does not behave completely unexpected, 1‰ of indirect CPV can not be excluded.

- we are looking at meson lifetimes to check whether HQE works
- if it does, we can have a look at $D \geq 12$ contributions (both lines cut)