Charm mixing in the Standard Model

ICHEP 2010 Paris

Markus Bobrowski, Institut für Theoretische Teilchenphysik (TTP)

Outline

- Introduction
- D^0 mixing in dimension 6 & 7
- $SU(3)_F$ breaking in higher dimensions
- Conclusions

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recent status of D^0 mixing: experiment

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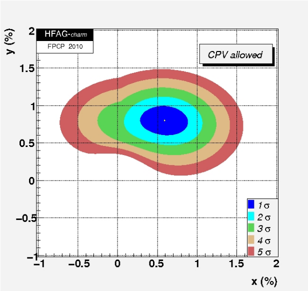
mixing parameters: $x = \frac{\Delta M}{\Gamma}$, $y = \frac{\Delta\Gamma}{2\Gamma}$

- HFAG average 2010
  - BaBar, Belle, CDF, CLEO

$$x = (0.59 \pm 0.20)\,\%$$
$$y = (0.80 \pm 0.13)\,\%$$

- new BaBar result
  - hep-ex/1004.5053

$$x = \left(1.6 \pm 2.3^{\text{stat.}} \pm 1.2^{\text{syst.}} \pm 0.8^{\text{model}}\right) \cdot 10^{-3}$$
$$y = \left(5.7 \pm 2.0^{\text{stat.}} \pm 1.3^{\text{syst.}} \pm 0.7^{\text{model}}\right) \cdot 10^{-3}$$



recent status of D^0 mixing: theory

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exclusive approach

▷ Falk, Grossman, Ligeti and Petrov ('02); Falk, Grossman, Ligeti, Nir, & Petrov ('04)

- sum over intermediate hadronic states

  LIMITATIONS: needs a lot of decay amplitudes & strong phases at high precision

  ⇓

  e.g. estimate contribution from $SU(3)_F$ breaking in phase space assuming the absence of cancellations between

  - $SU(3)_F$ breaking from phase space & matrix elements
  - different $SU(3)_F$ multipletts

  TYPICALLY... $y = \mathcal{O}(1\%)$ considered as natural

inclusive approach

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

- OPE of $\Delta C = 2$ effective Hamiltonian

  LIMITATIONS: relies on $m_c \gg \Lambda$ and quark-hadron duality

  TYPICALLY... $x, y \lesssim 10^{-3}$

neutral meson oscillations

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- neutral meson oscillations

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

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Heavy quark expansion (HQE)

expand the decay width matrix as a series of local operators of increasing dimension (series expansion in Λ/m_c)

$$\hat{\Gamma} \propto \mathrm{Im}\, i \int \mathrm{d}^4x \, \langle \mathrm{T}\, \mathcal{H}(x)\, \mathcal{H}(0) \rangle = \sum_{\dim n = 0}^{\infty} \left(\frac{\Lambda}{m_c}\right)^n \mathbf{G}_n \, \langle \mathbf{Q}_n \rangle$$

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- diagonalisation $\rightsquigarrow$ stationary states

$$(\Delta M)^2 - \frac{1}{4}(\Delta\Gamma)^2 = 4|M_{12}|^2 - |\Gamma_{12}|^2,$$

$$\Delta M\,\Delta\Gamma = 4|M_{12}|\,|\Gamma_{12}|\,\cos\phi$$

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

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Γ_{12} in the HQE

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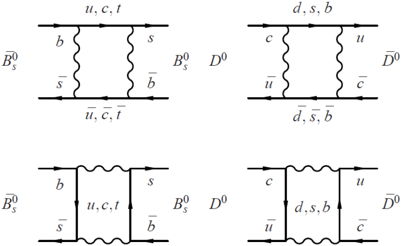
Heavy quark expansion of Γ_{12}

$$\Gamma_{12} = \Gamma_0 + \left(\frac{\Lambda}{m_c}\right)^2 \Gamma_2 + \left(\frac{\Lambda}{m_c}\right)^3 \Gamma_3 + \left(\frac{\Lambda}{m_c}\right)^4 \Gamma_4 + \ldots$$

- QCD: $\Gamma_i = \Gamma_i^{(0)} + \frac{\alpha_s}{\pi}\Gamma_i^{(1)} + \ldots$

- $D = 7$ corrections $\Gamma_4^{(0)}$
  - ▷ **Beneke, Buchalla, & Dunietz ('96); Dighe, Kim, Hurth, & Yoshikawa ('02)**
- $\mathcal{O}(\alpha_s)$ QCD corrections $\Gamma_3^{(1)}$ to the $D = 6$ diagrams
  - ▷ **Beneke, Buchalla, Greub, Lenz, & Nierste ('99); Ciuchini, Franco, Lubicz, Mescia, & Tarantino ('03); Beneke, Buchalla, Lenz, & Nierste ('03)**
- $D = 8$ corrections $\Gamma_5^{(0)}$
  - ▷ **Badin, Gabbiani, & Petrov ('07)**

SU(3)$_F$ symmetry and GIM mechanism I



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

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

$$\lambda_q \equiv V_{qs}^* V_{qb} \, (B_s^0) - \lambda_q \equiv V_{cq}^* V_{uq} \, (D^0)$$

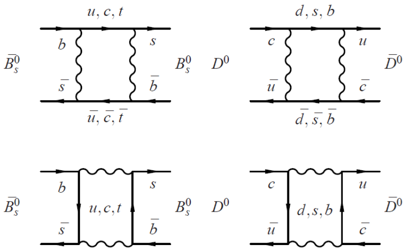
- CKM unitarity: $\lambda_d + \lambda_s + \lambda_b = 0$

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

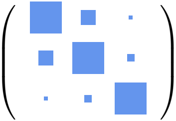
$$\Gamma_{12}(D^0) = -\lambda_s^2 \left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{ds} + \Gamma_{12}^{dd}\right) + 2\lambda_s\lambda_b \left(\Gamma_{12}^{ds} - \Gamma_{12}^{dd}\right) - \lambda_b^2 \, \Gamma_{12}^{dd}$$

$\rightsquigarrow$ reveals effects of CKM hierarchy and flavour symmetry

$SU(3)_F$ symmetry and GIM mechanism II



CKM hierarchy: $V_{\mathrm{CKM}} =$



GIM suppression

CKM hierarchy and residual $SU(3)_F$ symmetry require charm oscillations to be very slow.

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

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

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

$\mathbf{z}^2$ $\mathbf{z}$

$\lambda = \sin\theta_C \simeq 0.2255$

charm mixing in $D = 6, 7$ – numerical results

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$$\Gamma_{12}(D^0) = -\lambda_s^2 \underbrace{\left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{sd} + \Gamma_{12}^{dd}\right)}_{1.15\,\bar{z}^2 - 59.7\,\bar{z}^3} + 2\lambda_s\lambda_b \underbrace{\left(\Gamma_{12}^{sd} - \Gamma_{12}^{dd}\right)}_{-2.75\,\bar{z}} - \lambda_b^2 \underbrace{\Gamma_{12}^{dd}}_{1.96}$$

- $$\begin{aligned} 10^7\Gamma_{12} &= -14.0083 + 0.0009\,i && \text{1}^{\text{st}}\text{ term: } \mathcal{O}(\lambda^{9.0}) \\ &\quad -6.65 - 15.7\,i && \text{2}^{\text{nd}}\text{ term: } \mathcal{O}(\lambda^{8.9}) \\ &\quad 0.28 - 0.29\,i && \text{3}^{\text{rd}}\text{ term: } \mathcal{O}(\lambda^{11}) \\ &= \mathbf{-20.4 - 16.0\,i} \end{aligned}$$

▷ **MB, A. Lenz, J. Riedl, J. Rohrwild. JHEP 03 (2010), 009.**

$$\frac{\text{HQE } D = 6, 7 \text{ (SM)}}{\text{HFAG}} = 10^{3\ldots4}$$

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the weak phase in Γ_{12}

- folklore... set $\lambda_b \simeq 0$

  $\Downarrow$

  negligible phase in Γ_{12}:
  $\arg \lambda_s^2 \simeq 10^{-4}$
- keeping 2nd & 3rd term:

  $\arg \Gamma_{12} = 0.5 \ldots 2.6$

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  - QCD $\propto \alpha_s(m_c)$ large

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  long-distance dynamics (violation of quark hadron duality)

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within HQE

- in the SM: $SU(3)_F$ breaking effects, enhancing

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

▷ **higher orders of the HQE**

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  - violating 3×3 CKM unitarity

    ▷ **factor $\mathcal{O}(10)$ with a 4^{th} generation:**

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beyond HQE?

▷ **invoke meson lifetimes to test the applicability of the HQE approach to the charm sector**

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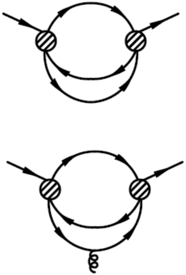
a consistency test for the HQE



meson lifetimes

- not affected by GIM $\Rightarrow$ HDO & NP effects small
- ideal testing ground for the HQE

work in progress!

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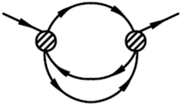

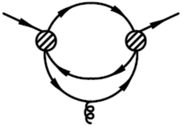

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- naïve estimate for deviation from LO/HQE: lifetime-ratios of D^0, D^+, and D_s^+ mesons
- set $\Gamma = \Gamma_0(c)\,(1+\delta)$ and use $\Pi_{\mathrm{fs}}(D^+) = \Pi_{\mathrm{fs}}(D_s^+)$

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

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

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

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

hadronic uncertainties cancel!

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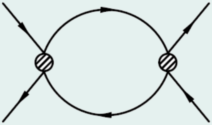
breaking $SU(3)_F$ flavour interference

$D \geq 6$



- origin of $SU(3)_F$ suppression in $D = 6, 7$:

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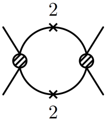
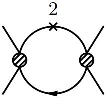


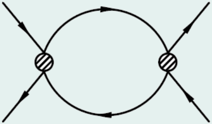
z^2



z

breaking $SU(3)_F$ flavour interference

D ≥ 6



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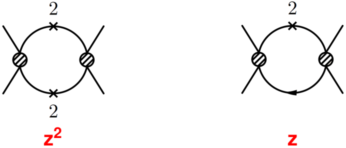


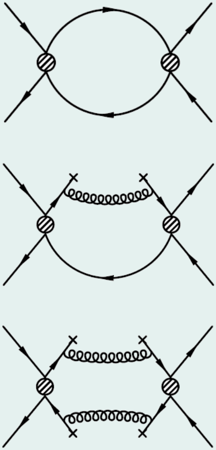
  - one mass insertion to break flavour symmetry
  - 2nd one to compensate chirality flip

breaking $SU(3)_F$ flavour interference

$D \geq 6$

$D \geq 9$

$D \geq 12$



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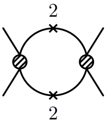

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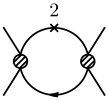
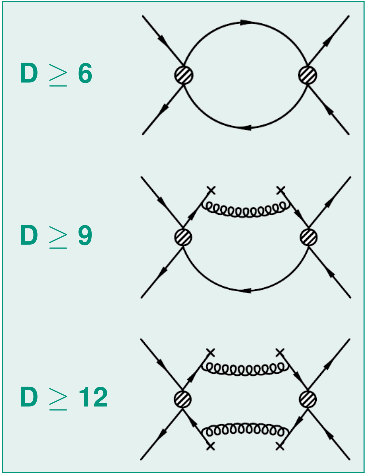


z

  - one mass insertion to break flavour symmetry
  - 2nd one to compensate chirality flip
- break 1 order of $SU(3)_F$ interference by cutting one internal line
- dominance of $D = 9, 12$ of the HQE

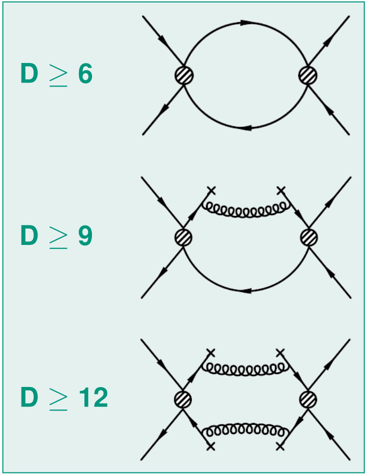
▷ Georgi ('92), Ohl, Ricciardi, & Simmons ('93), Bigi & Uraltsev ('01)

factorisation of 6-quark operators



- estimate matrix elements of 6-quark operators

factorisation of 6-quark operators



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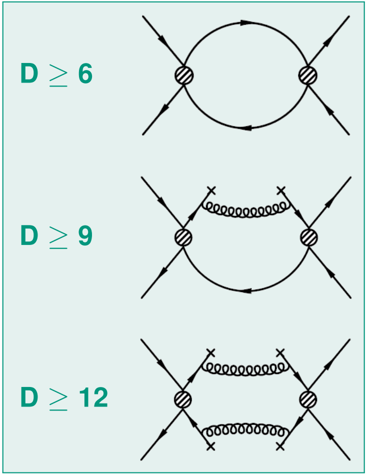

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$\Downarrow$

sea quark & gluon content modelled with the vacuum condensate, neglect higher excitations in the meson state

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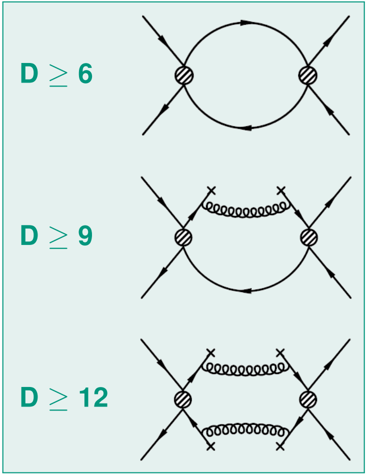

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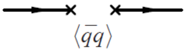
- $\langle \bar{q}q \rangle$ correction $\delta\,\Gamma_{12}$ can be expanded in terms of 4-quark operators

$$\hat{Q} = (\overline{u}\,c)_{V-A} \otimes (\overline{u}\,c)_{V-A}$$
$$\hat{Q}_S = (\overline{u}\,c)_{S+P} \otimes (\overline{u}\,c)_{S+P}$$

diquark condensate intermediate states

- quark condensate background



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

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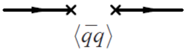
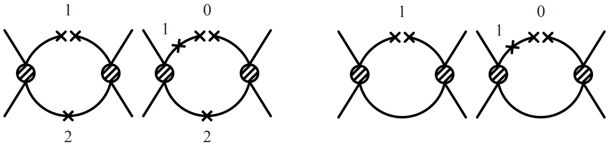
- quark condensate background



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

- SU(3)$_F$ breaking

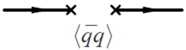
$$\delta\Gamma_{12} = -\lambda_s^2 \left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{ds} + \Gamma_{12}^{dd} \right) + 2\lambda_s\lambda_b \left(\Gamma_{12}^{ds} - \Gamma_{12}^{dd} \right) - \lambda_b^2\, \Gamma_{12}^{dd}$$



$z^{\frac{3}{2}}$ $\qquad$ $\sqrt{z}$

diquark condensate intermediate states

- quark condensate background



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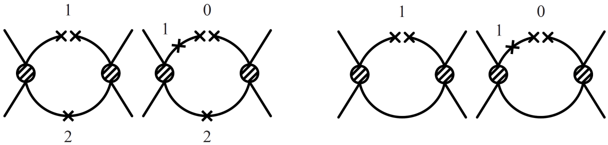
- SU(3)$_F$ breaking

has to overcome generic suppression $\sim 4\pi\alpha_s \frac{\langle \bar{s}s \rangle}{m_c^3} \simeq 0.3$

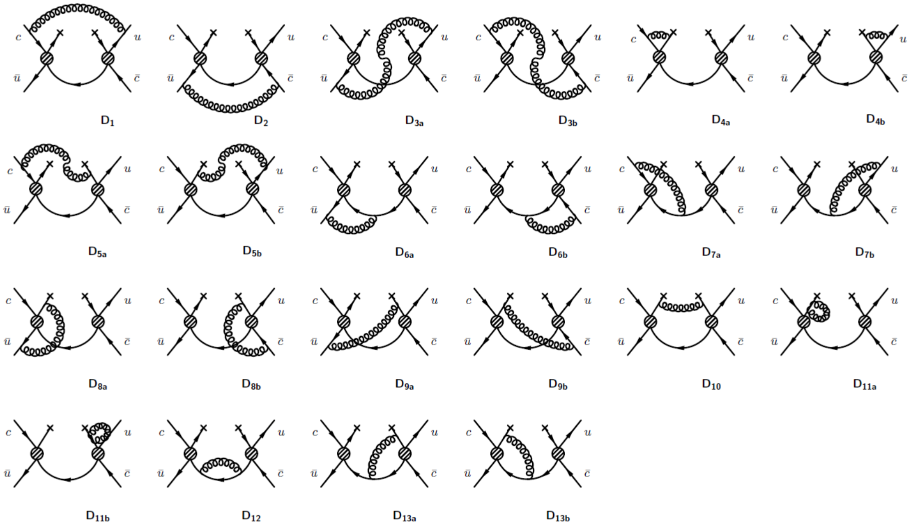
$$\delta\Gamma_{12} = -\lambda_s^2 \boxed{\left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{ds} + \Gamma_{12}^{dd}\right)} + 2\lambda_s\lambda_b \boxed{\left(\Gamma_{12}^{ds} - \Gamma_{12}^{dd}\right)} - \lambda_b^2 \boxed{\Gamma_{12}^{dd}}$$



$z^{\frac{3}{2}}$ $\sqrt{z}$

$\Rightarrow$ diquark condensate removes one power of m_s/m_c

diquark condensate intermediate states



numerical results

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- GIM cancellations softer in $D = 10/12$

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

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- flavour symmetry breaking:

$$\Gamma_{12}^{ss} = 1.908 + 0.036 \qquad (+1.9\%)$$

$$\Gamma_{12}^{sd} = 1.935 + 0.018 \qquad (+0.9\%)$$

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$$\delta\,\Gamma_{12} = -\lambda_s^2 \underbrace{\delta\left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{ds} + \Gamma_{12}^{dd}\right)}_{0.43\,\bar{z}^{\frac{3}{2}}} + 2\lambda_s\lambda_b \underbrace{\delta\left(\Gamma_{12}^{ds} - \Gamma_{12}^{dd}\right)}_{0.19\,\bar{z}^{\frac{1}{2}}} - \lambda_b^2 \underbrace{\delta\,\Gamma_{12}^{dd}}_{0}$$

$\times 13$ $\quad\quad$ $\times 0.66$

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

$\times 8.5$

▷ MB, Braun, Lenz, Nierste, Prill ('10)

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▷ **MB, Braun, Lenz, Nierste, Prill ('10)**

- weak phase in the absorptive part: $\arg\Gamma_{12} \simeq 3\%$

Outline

- Introduction
- D^0 mixing in dimension 6 & 7
- $SU(3)_F$ breaking in higher dimensions
- Conclusions

summary & outlook

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- options for the dominant contribution to Γ_{12}:
  - QCD: flavour symmetry breaking in higher orders of the HQE
  - QCD beyond HQE (~~QHD~~)
  - new physics
- $D = 10/12$ enhanced by a factor $\mathcal{O}(10) \Rightarrow \mathrm{SU}(3)_\mathrm{F}$ breaking mechanism works
- weak phase $\arg \Gamma_{12} = \mathcal{O}(1\%)$ is not unnatural in the SM
- useful next steps:
  - calculate meson lifetimes to check HQE
  - other condensate topologies, such as $\langle (\bar{q}\, q)\, (\bar{q}\, q) \rangle$, $\langle \bar{q}\, G\, q \rangle$, $\langle G\, G \rangle$

    $\rightsquigarrow$ **enhancement** $\times \mathcal{O}(100)$**?**
  - calculate M_{12}

backup slides

stationary state labels

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- stationary neutral meson eigenstates can be labeled as
  - heavy/light
  - short/long
  - predominantly CP even/odd
- $$\Gamma_{\mathrm{CP}\pm} = \sum_f \mathcal{N}_f \left| \langle f \,|\, D_\pm \rangle \right|^2 = \Gamma \mp \mathrm{Re}\,\Gamma_{12}$$

  ▷ Dunietz, Fleischer, & Nierste ('01)

$$D_+ = D_{\mathrm{sh}}$$
$$D_- = D_{\mathrm{lg}}$$

- in accordance with *Belle* measurement

$$y_{\mathrm{CP}} = \frac{\Gamma\left(D^0 \to K^+K^-\right)}{\Gamma\left(D^0 \to K^-\pi^+\right)} - 1 > 0$$

▷ Starič & al. ('07); Bergmann, Grossman, Ligeti, Nir, & Petrov ('00)