$D - \bar{D}$-Mixing and CP Violation

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in collaboration with

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Summary

The statement/textbook-wisdom

“CP-violation (in mixing) of the order of one per mille is an unambigous signal for new physics”

is **currently not justified.**

More theoretical work has to be done to shrink the allowed region for CP-violation within in the SM

- It was a hard fight to convince people!
  — 6 Referee reports before published in JHEP —
- A.A.Petrov at CKM2010:
  at most $\approx 10^{-3}$ in the SM; 10^{-2} is a “smoking gun” signature of NP

Outline

Introduction: D mixing

Theoretical approaches for D mixing

HQE for the D system?

- **Naive look at lifetimes**
- **Mixing:** $D = 6$
- **Mixing:** $D > 6$
- **Mixing: New Physics**

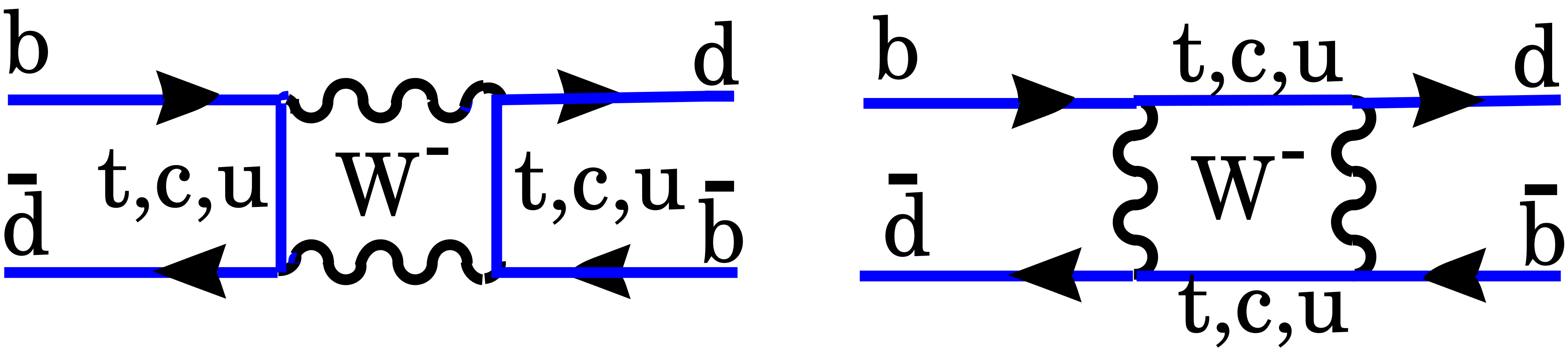
Outlook

Mixing Formalism I

Time evolution of a decaying particle: $B(t) = \exp\left[-im_B t - \Gamma_B/2t\right]$
can be written as

$$i\frac{d}{dt}\begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix} = \left(\hat{M} - \frac{i}{2}\hat{\Gamma}\right)\begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix}$$

BUT: In the neutral B-system transitions like $B_{d,s} \to \bar{B}_{d,s}$ are possible due to weak interaction: **Boxdiagrams**



$\Rightarrow$ **off-diagonal elements** in $\hat{M}$, $\hat{\Gamma}$: M_{12}, Γ_{12} (complex)

Diagonalization of $\hat{M}$, $\hat{\Gamma}$ gives the physical eigenstates B_H and B_L with the masses M_H, M_L and the decay rates Γ_H, Γ_L red

CP-odd: $B_H := p\,B + q\,\bar{B}$, CP-even: $B_L := p\,B - q\,\bar{B}$ with $|p|^2 + |q|^2 = 1$

Mixing Formalism II

$|M_{12}|$, $|\Gamma_{12}|$ and $\phi = \text{arg}(-M_{12}/\Gamma_{12})$ can be related to three observables:

- **Mass difference:** $\Delta M := M_H - M_L = 2|M_{12}| \left(1 + \frac{1}{8}\frac{|\Gamma_{12}|^2}{|M_{12}|^2}\sin^2\phi + ...\right)$
  $|M_{12}|$: heavy internal particles: t, SUSY, ...

- **Decay rate difference:** $\Delta\Gamma := \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos\phi \left(1 - \frac{1}{8}\frac{|\Gamma_{12}|^2}{|M_{12}|^2}\sin^2\phi + ...\right)$
  $|\Gamma_{12}|$: light internal particles: u, c, ... (almost) no NP!!!

- **Flavor specific/semileptonic CP asymmetries:**
  $\bar{B}_q \to f$ and $B_q \to \bar{f}$ forbidden
  No direct CP violation: $|\langle f|B_q\rangle| = |\langle \bar{f}|\bar{B}_q\rangle|$
  e.g. $B_s \to D_s^- \pi^+$ or $B_q \to X l \nu$ (*semileptonic*)

$$a_{sl} \equiv a_{fs} = \frac{\Gamma(\overline{B}_q(t) \to f) - \Gamma(B_q(t) \to \overline{f})}{\Gamma(\overline{B}_q(t) \to f) + \Gamma(B_q(t) \to \overline{f})} = -2\left(\left|\frac{q}{p}\right| - 1\right) = \text{Im}\frac{\Gamma_{12}}{M_{12}} = \frac{\Delta\Gamma}{\Delta M}\tan\phi$$

Introduction: D-mixing 1

- K^0**-mixing:** 1955 Lederman (measured different lifetimes)
- B_d**-mixing:** 1987 DESY
- B_s**-mixing:** 2006 TeVatron

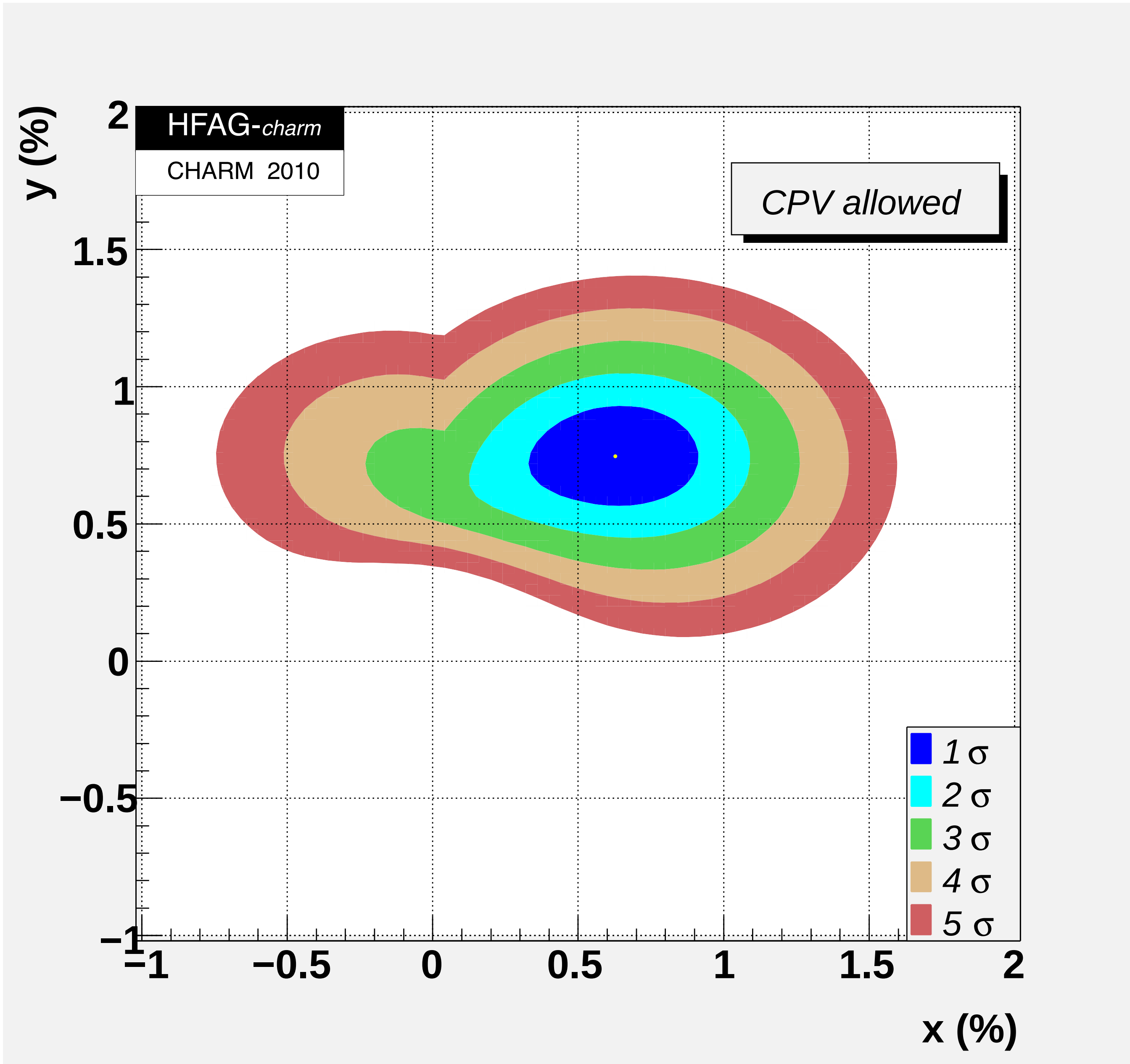
D-mixing is now also experimentally established

	1σ error	95% CL
$x := \frac{\Delta M}{\Gamma}$	$\left(0.63^{+0.19}_{-0.20}\right)\%$	$[0.24, 1.00]\%$
$y := \frac{\Delta \Gamma}{2\Gamma}$	$(0.75 \pm 0.12)\%$	$[0.51, 0.99]\%$

HFAG 2010 (BaBar, Belle, CDF, CLEO)

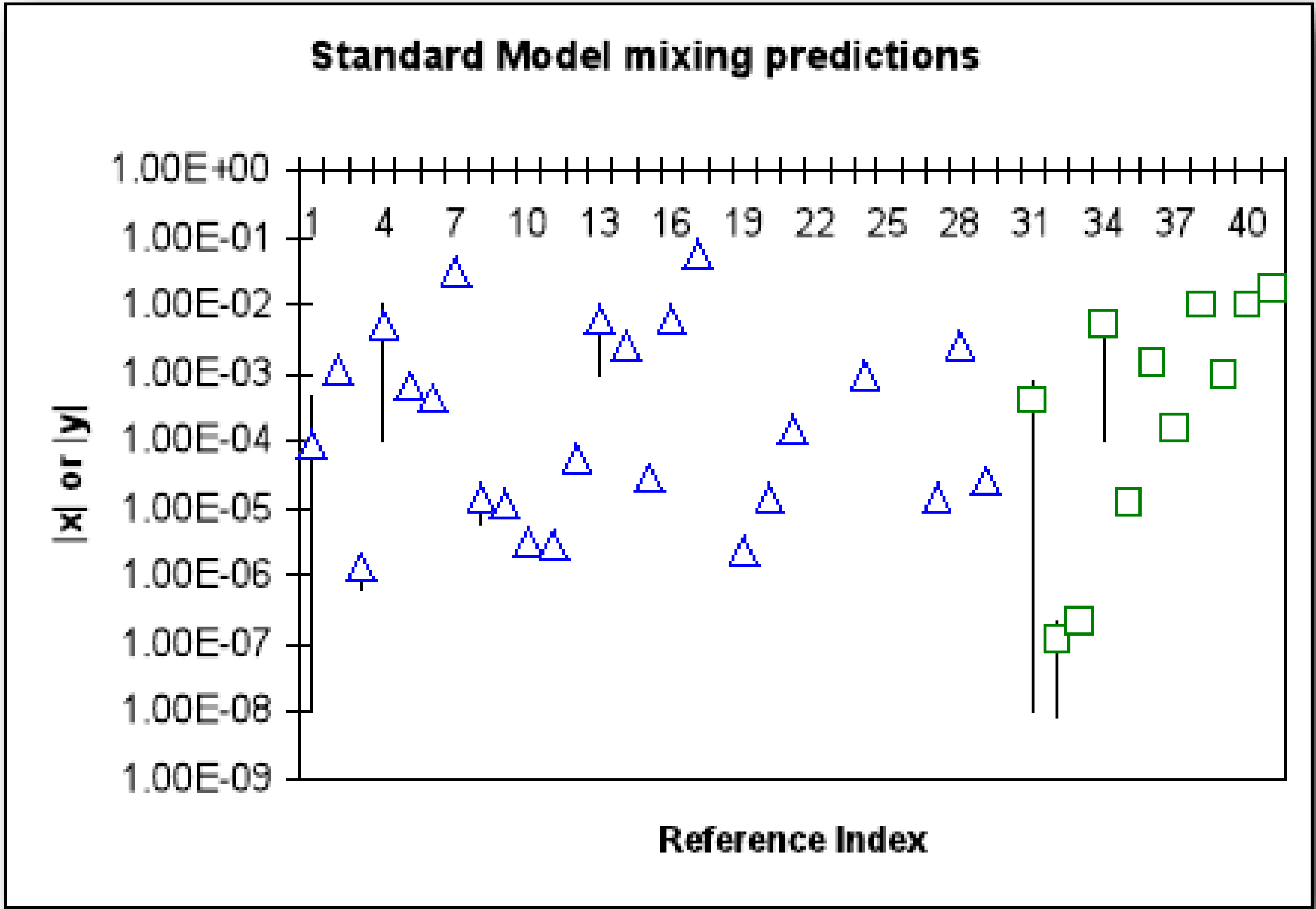
- No single experiment above 5 σ
- David Asner@CKM2010: The more precise, the less significant
- $\Rightarrow \Gamma_{12}/M_{12} \approx \mathcal{O}(1)$, i.e. not so nice formulas as in the B-case

Introduction: D-mixing 2



Introduction: D-mixing 3

Theory fails? (grabbed from a talk of Alexey Petrov)



Theory I

D mixing vs. B_s, B_d and K-mixing

1. **internal down-type quarks** in the box diagrams
2. the theory is **much more complicated**!

There are two approaches to describe the SM contribution to D-mixing

- **Exclusive Approach**
  Falk, Grossman, Ligeti, Petrov PRD65 (2002)
  Falk, Grossman, Ligeti, Nir, Petrov PRD69 (2004)
- **Inclusive Approach**
  Georgi, PLB 297 (1992) Ohl, Ricciardi, Simmons, NPB 403 (1993)
  Bigi, Uraltsev, NPB 592 (2001)

State of the art, but more an estimate than a calculation

$\Rightarrow$ x, y up to 1% not excluded

$\Rightarrow$ Essential no CPV in mixing — unambiguous signal for NP!!!

Theory II - Exclusive approach

y due to final states common to D and $\overline{D}$

$$y = \frac{1}{\Gamma} \sum_n \rho_n \langle \overline{D}^0 | \mathcal{H}_W^{\Delta C=1} | n \rangle \langle n | \mathcal{H}_W^{\Delta C=1} | D^0 \rangle$$

Much too complicated to calculate exclusive decay rates exactly!

- Estimate only SU(3) violating phase space effects (mild assumptions about $\vec{p}$-dependence of matrix elements) = calculable source of SU(3) breaking
- **Assume** hadronic matrix elements are SU(3) invariant
- **Assume** CP invariance of D decays
- **Assume** no cancellations with other sources of SU(3) breaking
- **Assume** no cancellations between different SU(3) multipletts

$\Rightarrow$ individual effects of 1% possible: $y^{Exp} \approx 1\% \not\Rightarrow$ NP

- "our analysis does not amount to a SM calculation of y”

Theory III - “Phenomenological” approach

See talk of Hai-Yang Cheng:

“There is no QCD based theory fo hadronic decays because $1/m_c$ is large
$\Rightarrow$ rely more on data than theory

$$x \approx 10^{-3} \qquad y \approx \text{few} \times 10^{-3}$$

Cheng, Chiang PRD81,114020

Our approach:

Do not give up yet

Try to push QCD to its limits

Theory IV - Inclusive approach

Systematic expansion of the decay rate in powers of m_b^{-1} yields

$$\Gamma = \Gamma_0 + \frac{\Lambda^2}{m_b^2}\Gamma_2 + \frac{\Lambda^3}{m_b^3}\Gamma_3 + \ldots$$

Voloshin, Uraltsev, Khoze, Shifman, Vainshtein

Γ_0: Decay of a free quark $\Rightarrow$ all b-hadrons have the same lifetime

Γ_2: First corrections due to kinetic and chromomagnetic operator

Γ_3: Weak annihilation and Pauli interference
Distinguish between different spectators $\Rightarrow$ Lifetime differences $\frac{\tau_1}{\tau_2}, \Delta\Gamma$
numerically enhanced by phase space factor $16\pi^2$

The use of the HQE for the D-system is questionable!

- Λ / m_c might be too large ($\Lambda \neq \Lambda_{QCD}$!)
- $\alpha_s(m_c)$ might be too large

Conclusion for the B-system

Investigation of $\tau(B^+)/\tau(B_d)$ and $\tau(B_s)/\tau(B_d)$

HQE seems to work very well!

But: still a lot of work to do!

- Lattice determination of non-perturbative parameters
- Perturbative determination of all contributions to baryon lifetimes
- ...

$\Rightarrow$ **Use HQE in the search for new physics in B mixing** CKMfitter; UTfit;...

SM is excluded by 3.8 σ A.L., Nierste, CKMfitter 1008.1593

Does it also work for the D-system?

Try HQE for the D-system

! This is just a naive estimate - a quantitative analysis has to be done!

Exp.: $\frac{\tau(D^+)}{\tau(D^0)} = \frac{1040\,\text{fs}}{410\,\text{fs}} \approx 2.5$ $\frac{\tau(D_s^+)}{\tau(D^0)} = \frac{500\,\text{fs}}{410\,\text{fs}} \approx 1.2$

- HQE for D-system
  - D^0: weak annihilation (=WA)
  - D^+, D_s^+: Pauli interference (=PI); PI $(D_s^+) = (V_{us}/V_{ud})^2$ PI (D^+)
- HQE for B-system
  - B_d, B_s: WA, similar CKM structure, differences due to phase space
  - B^+: PI (larger than WA)

$$\Gamma(D_x) = \Gamma(c) + \delta\Gamma(D_x)$$

The experimental constraints are full-filled for

$$\frac{\delta\Gamma(D^+)}{\Gamma(c)} \approx -53\%\,, \qquad \frac{\delta\Gamma(D^0)}{\Gamma(c)} \approx +19\%$$

This looks reasonable: $(m_b/m_c)^3 \approx 20...30$

Definitions for D-mixing

$$y := \frac{\Delta\Gamma}{2\Gamma_{D^0}}\,, \quad x := \frac{\Delta M}{\Gamma_{D^0}}.$$

Connection to box diagrams:

$$\begin{aligned} (\Delta M)^2 - \frac{1}{4}(\Delta\Gamma)^2 &= 4|M_{12}|^2 - |\Gamma_{12}|^2, \\ \Delta M\,\Delta\Gamma &= 4|M_{12}||\Gamma_{12}|\cos(\phi)\,. \end{aligned}$$

with $\phi := \arg[-M_{12}/\Gamma_{12}]$

If $|\Gamma_{12}/M_{12}| \ll 1$, as in the case of the B_s system ($\approx 5 \cdot 10^{-3}$) or if $\phi \ll 1$, one gets the famous approximate formulae

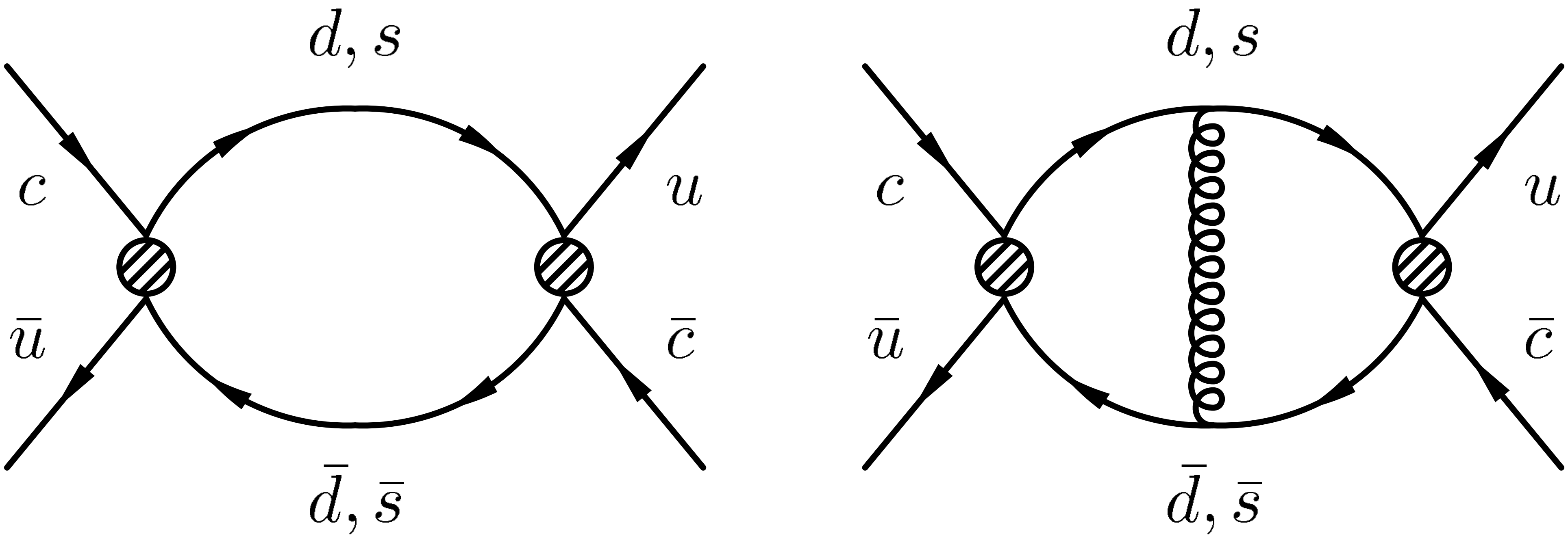
$$\Delta M = 2|M_{12}|\,, \qquad \Delta\Gamma = 2|\Gamma_{12}|\cos\phi\,.$$

In the D-system $|\Gamma_{12}/M_{12}| \approx 1$ possible — Solve Eigenvalue equation exactly

Estimate: $\Delta\Gamma \leq 2|\Gamma_{12}|$

SM predictions for Γ_{12} in D-mixing I

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



$$\begin{aligned}
\lambda_d &= V_{cd}V_{ud}^* = -c_{12}c_{23}c_{13}s_{12} - c_{12}^2 c_{13} s_{23} s_{13} e^{i\delta_{13}} = \mathcal{O}\left(\lambda^1 + i\lambda^5\right), \\
\lambda_s &= V_{cs}V_{us}^* = +c_{12}c_{23}c_{13}s_{12} - s_{12}^2 c_{13} s_{23} s_{13} e^{i\delta_{13}} = \mathcal{O}\left(\lambda^1 + i\lambda^7\right), \\
\lambda_b &= V_{cb}V_{ub}^* = c_{13} s_{23} s_{13} e^{i\delta_{13}} = \mathcal{O}\left(\lambda^5 + i\lambda^5\right),
\end{aligned}$$

SM predictions for Γ_{12} in D-mixing II

Common folklore $\lambda_b \approx 0$ (looks reasonable!)

Unitarity: $\lambda_d + \lambda_s = 0 \Rightarrow \Gamma_{12} = -\lambda_s^2 \left(\Gamma_{ss} - 2\Gamma_{sd} + \Gamma_{dd}\right)$

- **Γ_{12} vanishes in the SU(3)$_F$ limit**
  Use the results for B_s-mixing from Beneke, Buchalla, (Greub), A.L., Nierste 1998; 2003; Ciuchini, Franco, Lubicz, Mescia, Tarantino 2003, A.L., Nierste 2006

$$\Gamma_{ss} - 2\Gamma_{sd} + \Gamma_{dd} \approx 1.2 \frac{m_s^4}{m_c^4} - 59 \frac{m_s^6}{m_c^6}$$

Golowich, Petrov 2005, Bobrowski, A.L., Riedl, Rohrwild 2009

- **Γ_{12} is real to a very high accuracy**

$$\lambda_s^2 = \mathcal{O}\left(\lambda^2 + i\lambda^8\right) \Rightarrow \text{Arg}\left(\lambda_s^2\right) \approx \frac{1}{\lambda^6} \approx 10^{-4}$$

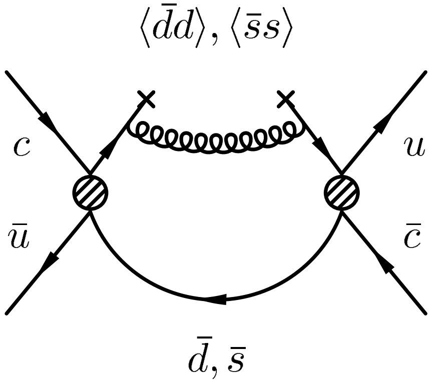
- **Overall result much too small**

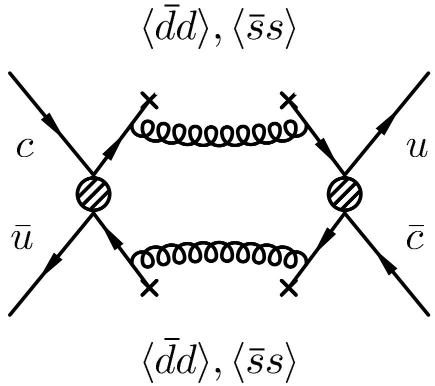
$$y \approx \mathcal{O}(10^{-6})$$

!!! Huge cancellations $\Rightarrow$ be careful with approximations !!!

SM predictions for Γ_{12} in D-mixing III

Idea: higher orders in HQE might be dominant if GIM is less pronounced





naive expectation for a single diagram:

y_D	no GIM	with GIM	
$D = 6,7$	$2 \cdot 10^{-2}$	$1 \cdot 10^{-6}$	Calculation
$D = 9$	$2 \cdot 10^{-2} ... 5 \cdot 10^{-4}$	???	Dimensional Estimate
$D = 12$	$2 \cdot 10^{-2} ... 1 \cdot 10^{-5}$	???	Dimensional Estimate

? Can one obtain $y_D^{Exp.}$?

?How big can ϕ be?

SM predictions for Γ_{12} in D-mixing IV

Our dimensional estimates

- Determine Γ_{12}: Imaginary part of 1-loop
- Estimate D = 9:
  - Quark condensate: $\langle \bar{s}s \rangle / m_c^3$
  - $4\pi\alpha_s$ relative to LO diagram
  - GIM : $(m_s/m_c)^3$ and m_s/m_c

Suppressed by about $2 \cdot 10^{-5}, 3 \cdot 10^{-3}$ compared to D=6 diagram
D=6 GIM suppressed by about $5 \cdot 10^{-5}$ $\Rightarrow$! IMPORTANT !

Dimensional estimate in Bigi, Uraltsev 2001

- Determine M_{12}: 0-loop
- Estimate D = 9: Quark condensate: $\mu^3_{hadron.}/m_c^3$ soft GIM : $m_s/\mu_{hadr.}$
- Estimate Γ_{12} via dispersion integral over M_{12}

Difference: $\frac{\langle \bar{s}s \rangle m_s}{m_c^4}$ vs. $\frac{m_s \mu^2_{hadron.}}{m_c^3}$ or better $\langle \bar{q}q \rangle \approx (0.24\text{GeV})^3$ vs. $\mu_{hadr.} \approx 1$ GeV

$\Rightarrow$ BU/BBLNP $\approx 80 \Rightarrow$ Calculation has to decide!

SM predictions for Γ_{12} in D-mixing V

Our Research Program

1. Redo D=6 without any approximations
   Bobrowski, A.L, Riedl, Rohrwild, JHEP 2010
2. Calculate D$\geq$9
   Bobrowski, A.L. 2010; Bobrowski, Braun, A.L., Nierste, Prill unpublished
3. Calculate D$\geq$12
4. Calculate M_{12}
5. Calculate lifetimes of D mesons
6. **Give a much more relieable range for the SM values of the possible size of CP violation in D mixing**

The failure of common folklore

D= 6,7 without folklore!!!! Bobrowski, A.L., Riedl, Rohrwild 2009, 2010

Unitarity: $\lambda_d + \lambda_s + \lambda_b = 0$

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

$$\begin{aligned} \Gamma_{sd}^{D=6,7} &= 1.8696 - 2.7616 \frac{m_s^2}{m_c^2} - 7.4906 \frac{m_s^4}{m_c^4} + \ldots . \\ \Gamma_{dd}^{D=6,7} &= 1.8696 \end{aligned}$$

$$\Gamma_{12} \propto \lambda_s^2 \frac{m_s^6}{m_c^6} + 2\lambda_s \lambda_b \frac{m_s^2}{m_c^2} - \lambda_b^2 \; 1$$

$$\begin{aligned} 10^7 \Gamma_{12}^{D=6,7} &= -14.6 + 0.0009i (\text{1st term}) -6.7 - 16i (\text{2nd term}) + 0.3 - 0.3i (\text{3rd term}) \\ &= -21.1 - 16.0i = (11 \ldots 39)\, e^{-i(0.5 \ldots 2.6)} . \end{aligned}$$

- **not zero in SU(3)$_F$ limit**
- **large phase ($\mathcal{O}(1)$) possible!!!**
- $y_D \in [0.5, 1.9] \cdot 10^{-6} \Rightarrow$ **still much smaller than experiment ($8 \cdot 10^{-3}$)**

SM predictions for Γ_{12} in D-mixing VII

What does this mean?

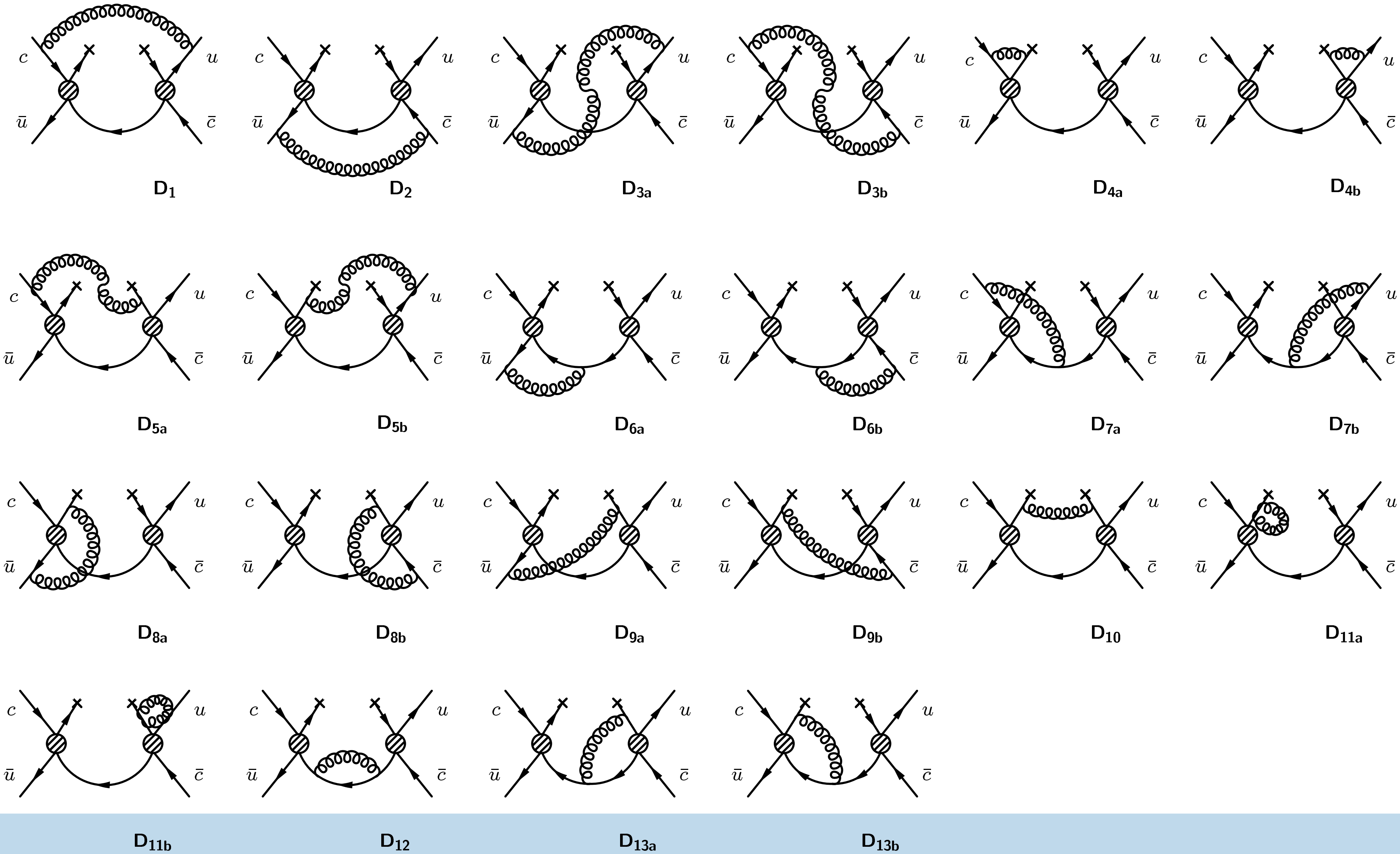
1. Standard argument for "arg Γ_{12} is negligible" is wrong

2. Can there be a sizeable phase in D-mixing?
   - Phase of Γ_{12} is unphysical
   - Phase of M_{12}/Γ_{12} is physical $\Rightarrow$ determine also M_{12}

3. $\Gamma_{12}^{D=6,7}$ has a large phase, but $y^{D=6,7} \ll y^{Exp.}$
   - Georgi 1992; Ohl, Ricciardi, Simmons 1993; Bigi, Uraltsev 2001
     Higher orders in the HQE might be dominant: $y^{D\geq 9} = y^{Exp.}$ not excluded
   - Bobrowski, A.L., Riedl, Rohrwild 2009, 2010
     If estimate of Bigi/Uraltsev is correct + our findings for D=6:
     $y^{Theorie} = y^{Exp.}$ and 5 per mille CP-violation not excluded
   - Bobrowski, A.L. 2010; Bobrowski, Braun, A.L., Nierste, Prill in progress
     Do the real calculation for $D \geq 9$

SM predictions for Γ_{12} in D-mixing VIII

Determination of D= 9,10,... in factorization approximation



SM predictions for Γ_{12} in D-mixing IX

Determination of D= 9,10,... in factorization approximation

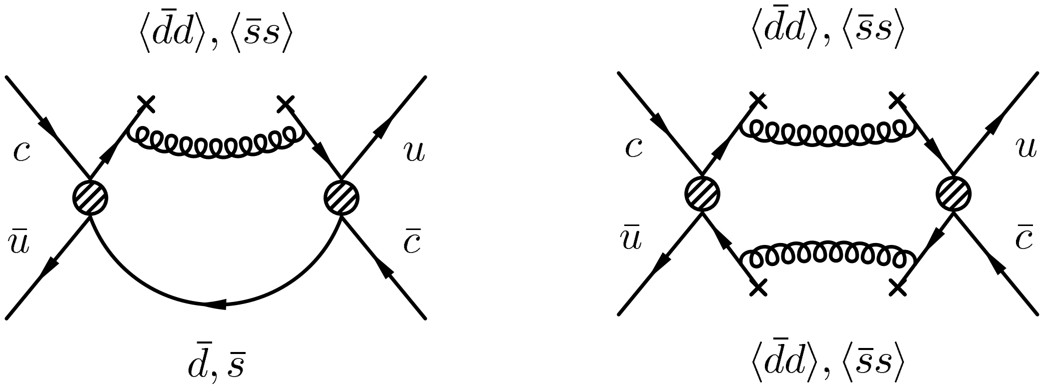
- Factorization approximation, expected to hold up to $1/N_c$
- Enhancement of $\mathcal{O}(15)$ compared to leading term
  Large effect, but not as large as estimated by Bigi, Uraltsev
- GIM cancellation reduced to: $\propto m_s^3$

$$\Gamma_{12} \quad \propto \quad \lambda_s^2 \cdot \frac{m_s^6}{m_c^6} + 2\lambda_s\lambda_b \cdot \frac{m_s^2}{m_c^2} + \lambda_b^2 \cdot 1$$

$$\rightarrow \Gamma_{12} \quad \propto \quad \lambda_s^2 \cdot \frac{m_s^3}{m_c^3} + 2\lambda_s\lambda_b \cdot \frac{m_s^2}{m_c^2} + \lambda_b^2 \cdot 1$$

SM predictions for Γ_{12} in D-mixing III

Idea: higher orders in HQE might be dominant if GIM is less pronounced



naive expectation for a single diagram:

y_D	no GIM	with GIM	CP violation	
$D = 6, 7$	$2 \cdot 10^{-2}$	$1 \cdot 10^{-6}$	$\mathcal{O}(1)$	Calculation
$D = 9$	$2 \cdot 10^{-2} ... 5 \cdot 10^{-4}$	$1.5 \cdot 10^{-5}$	$\mathcal{O}(5\%)$	Calculation
$D = 12$	$2 \cdot 10^{-2} ... 1 \cdot 10^{-5}$	???		Dimensional Estimate

? Can one obtain $y_D^{Exp.}$? ?How big can ϕ be?

Outlook

Careful investigation of the HQE terms

- **Brand-New:** Standard argument for negligible phase in Γ_{12} seems not to work
- **New :** Γ_{12} sensitive to NP Petrov et al
- **Text-Book-Wisdom:** Overall value much too small

Finish HQE estimates (incl. higher orders) of D-mixing and lifetimes

If y^{Theory} stays small: Interesting options:

a) HQE does not work in the D-system

b) Actual exp. value for y is very small (> 5 σ)
$\Rightarrow$ Theoreticians dream: Real prediction $\neq$ post-diction

c) **New physics is acting in the D-system**

c1) SU(3) suppression is much less pronounced

c2) unitarity of 3x3 CKM matrix is violated

New physics in D-mixing I

Contrary to expectation: Γ_{12} is sensitive to new physics!!!

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

Γ_{12} is small, because

1. $\Gamma_{ss} - 2\Gamma_{sd} + \Gamma_{dd}$ is small
2. λ_b is small

$\Rightarrow$ 2 possibilities for enhancements

1. Enhance $\Gamma_{ss} - 2\Gamma_{sd} + \Gamma_{dd}$
   see talk by Alexey Petrov
2. "Enhance λ_b"
   see next slides

New physics in D-mixing II

The most simple (boring?) extension of the SM: fourth generation SM4

- Obvious effect: New particles (b', t') in the box diagrams for M_{12}
- Often not seen: huge cancellations possible - $\delta V_{td,ts,tb}$ vs. (b', t')

$$\Delta_{B_s} = \frac{M_{12,SM4}^{B_s}}{M_{12,SM3}^{B_s}} = 1 + \frac{M_{12,SM4}^{tt,B_s} - M_{12,SM3}^{B_s}}{M_{12,SM3}^{B_s}} + \frac{M_{12,SM4}^{tt'+t't',B_s}}{M_{12,SM3}^{B_s}} .$$

Check allowed parameter range for V_{CKM4}: e.g. possible ($V_{tb} = 0.93$)

$$\Delta_{B_s} = 1 + (1.2044 - 0.6715i) + (-1.3434 - 0.0354i) = 1.11 \cdot e^{-i39^\circ},$$

- Overseen: Large Effects in Γ_{12} in D-mixing possible

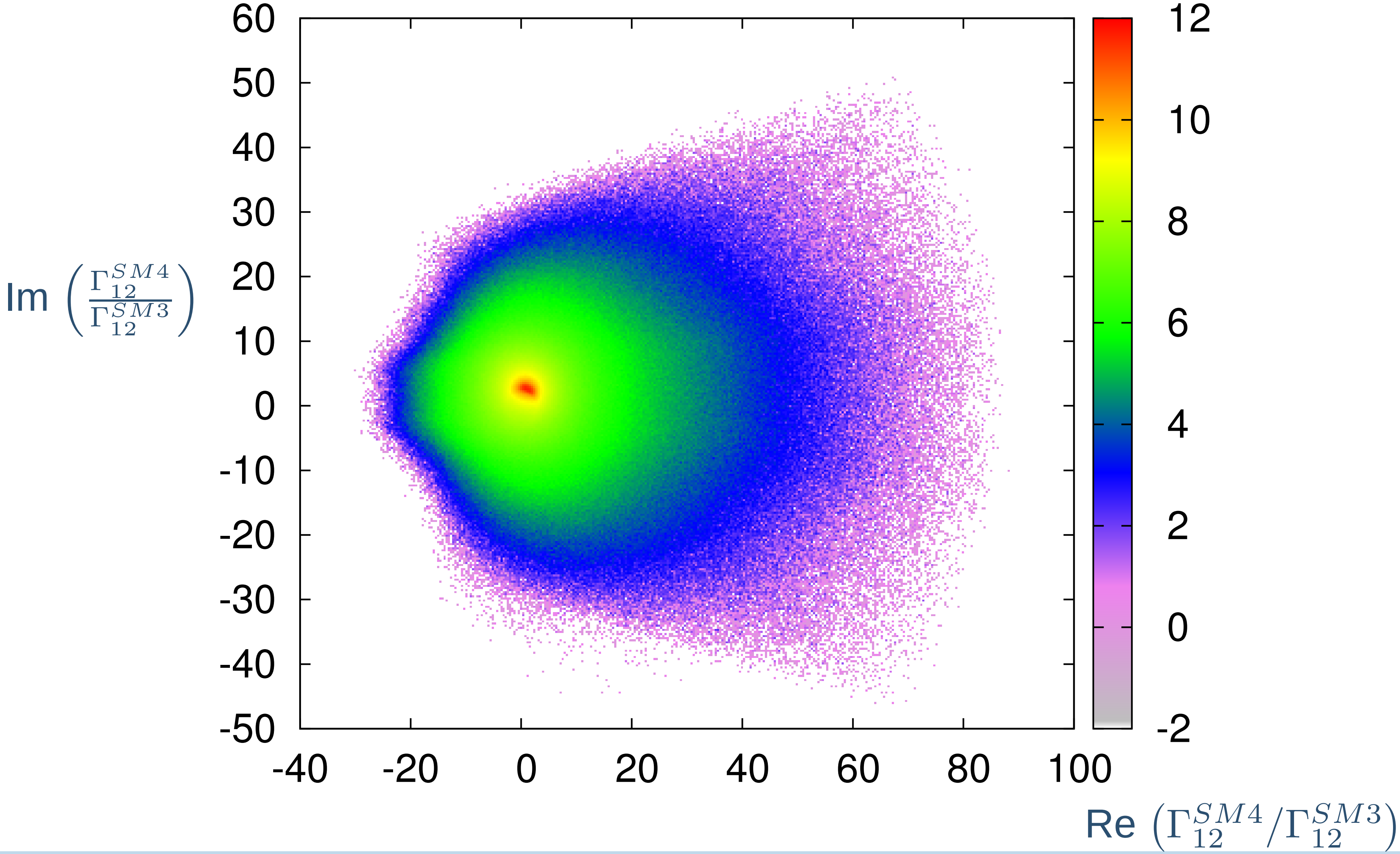
$$\Gamma_{12} = -\lambda_s^2 \left(\Gamma_{ss} - 2\Gamma_{sd} + \Gamma_{dd}\right) + 2\lambda_s (\lambda_b + \lambda_{b'}) \left(\Gamma_{sd} - \Gamma_{dd}\right) - (\lambda_b + \lambda_{b'})^2 \Gamma_{dd}$$

$\lambda_b \propto \lambda^{5...6}$ - still possible $\lambda_{b'} \propto \lambda^3$ (arXiv:0902.4883)

see also Melic et al, Kou et al., Soni et. al, Hou et al. ...

New Physics in D-Mixing III

Bobrowski, A.L., Riedl, Rohrwild; 0904.3971



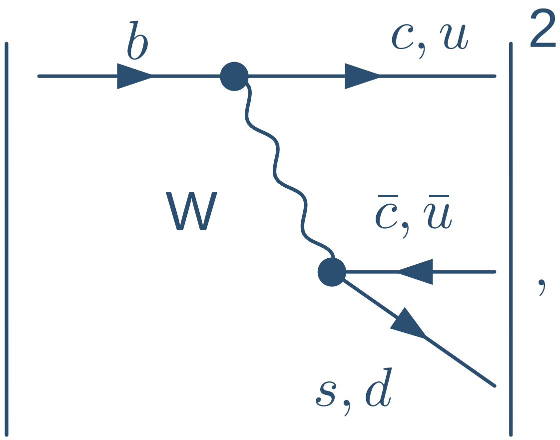
Inclusive Decays I*

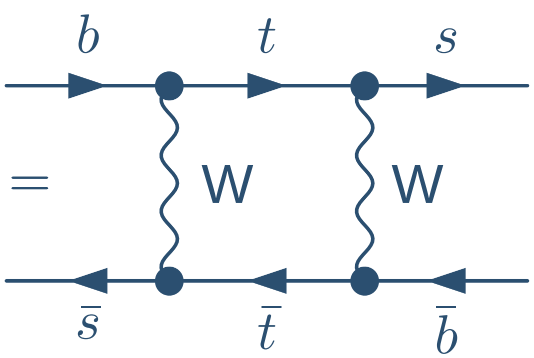
Theoretical determination of observables

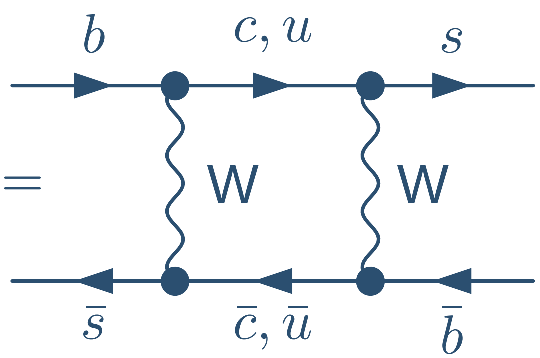
$$\frac{1}{\tau} = \sum_X \Gamma(B \to X)\,, \qquad \Delta M = 2|M_{12}|\,, \qquad \Delta\Gamma = 2|\Gamma_{12}|\cos(\phi)\,,$$

$$a_{sl} = \Im\left(\frac{\Gamma_{12}}{M_{12}}\right)\,, \qquad \phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)\,.$$

These quantities correspond to the following SM diagrams

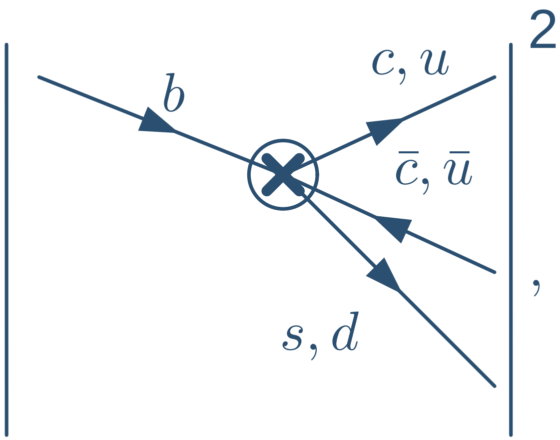
$\Gamma = \int \sum_X$ 

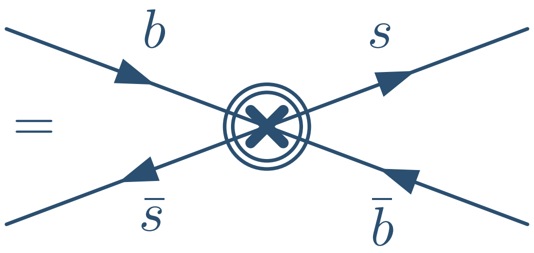
, $M_{12} =$ 

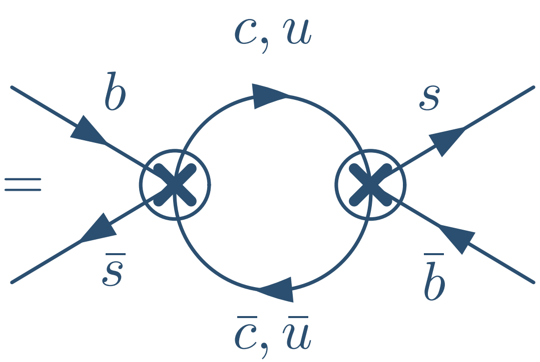
, $\Gamma_{12} =$ 

Inclusive Decays II*

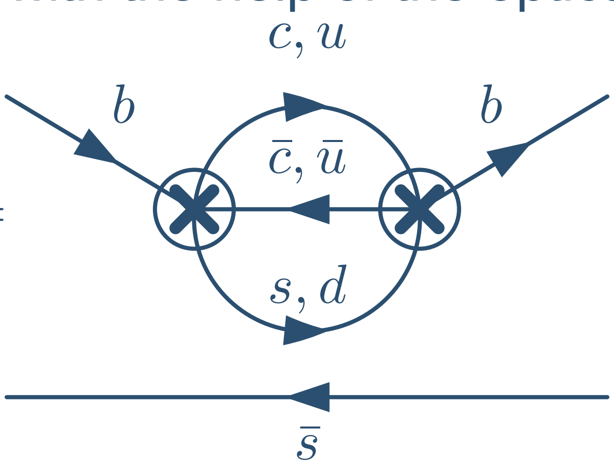
Use the fact: $m_t, M_W \gg m_b$ - integrate out heavy particles

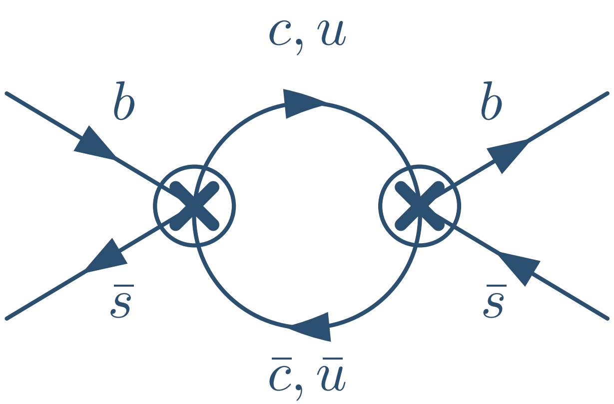
$\Gamma = \int \sum_X$


, $M_{12} =$


, $\Gamma_{12} =$


Rewrite Γ with the help of the optical theorem

$\Gamma =$


$+ \ldots +$


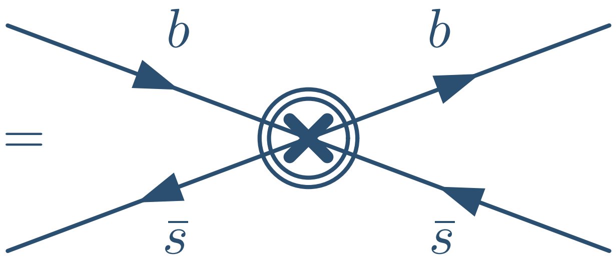
$+ \ldots$

Γ_0 Γ_3

Inclusive Decays III*

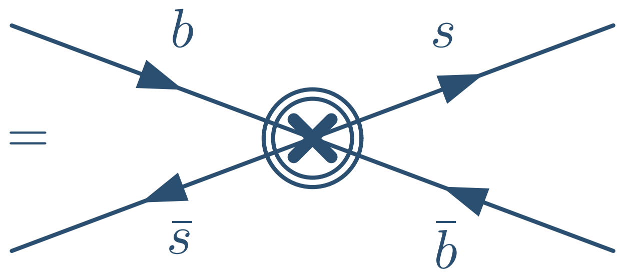
Use the fact: $m_b \gg \Lambda_{QCD}$ for Γ_0, Γ_3 and Γ_{12} - also local operators

$\Gamma_3 =$



,

$\Gamma_{12} =$



- Γ, M_{12} and Γ_{12} are expressed in terms of local $\Delta B = 0, 2$-operators
- Determination of Γ_3 and Γ_{12} almost identical
- **OPE II might be questionable - quark hadron duality**

  $\Rightarrow$ **test reliability of OPE II via lifetimes (no NP effects expected)**

  $\Rightarrow$ **calculate corrections in all possible “directions”, to get a feeling for the convergence**

Heavy Quark Expansion*

Systematic expansion of the decay rate in powers of m_b^{-1} yields

$$\Gamma = \Gamma_0 + \frac{\Lambda^2}{m_b^2}\Gamma_2 + \frac{\Lambda^3}{m_b^3}\Gamma_3 + \ldots$$

Voloshin, Uraltsev, Khoze, Shifman, Vainshtein

Γ_0: Decay of a free quark $\Rightarrow$ all b-hadrons have the same lifetime

Γ_2: First corrections due to kinetic and chromomagnetic operator

Γ_3: Weak annihilation and Pauli interference
Distinguish between different spectators $\Rightarrow$ Lifetime differences
numerically enhanced by phase space factor $16\pi^2$

State of the art*

Meson vs Meson

$$\frac{\tau_1}{\tau_2} = 1 + \quad \frac{\Lambda^3}{m_b^3}\left(\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{(1)} + \ldots\right) + \quad \frac{\Lambda^4}{m_b^4}\left(\Gamma_4^{(0)} + \ldots\right) + \ldots$$

Baryon vs Meson

$$\frac{\tau_1}{\tau_2} = 1 + \quad \frac{\Lambda^2}{m_b^2}\left(\Gamma_2^{(0)} + \ldots\right) + \quad \frac{\Lambda^3}{m_b^3}\left(\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{(1)} + \ldots\right) + \quad \frac{\Lambda^4}{m_b^4}\left(\Gamma_4^{(0)} + \ldots\right) + \ldots$$

Neutral Mesons

$$\frac{\Delta\Gamma}{\Gamma} = \quad \frac{\Lambda^3}{m_b^3}\left(\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{(1)} + \ldots\right) + \quad \frac{\Lambda^4}{m_b^4}\left(\Gamma_4^{(0)} + \ldots\right) + \ldots$$

$$\boxed{\Gamma_i^{(j)} = C_i^{(j)} \cdot \langle Q_i^{(j)} \rangle \propto f^2 \cdot B_i^{(j)} \cdot C_i^{(j)}}$$

Perturbative corrections

- $C_3^{(0)}$: '79...'92
- $C_4^{(0)}$: '96...'03
- $C_3^{(1)}$: '98...'03; incomplete for Λ_b
- $C_5^{(0)}$: '03...'06

non-perturbative corrections

$\langle Q_3 \rangle$: prel. $n_f = 2 + 1$ for B-mixing
only one determination for τ_{B+}/τ_{B_d}
only prel. studies for Λ_b

$\langle Q_4 \rangle$: mostly VIA

$\langle Q_5 \rangle$: only naive estimates

Strategy*

1. **Test reliability of the theoretical framework via lifetimes**

   — no NP effects expected —

2. **Currently no precise prediction of Γ_{12} and M_{12} possible**

   — compared to $\Delta M^{\text{Exp.}}$ —

3. **Cleaner SM prediction of Γ_{12}/M_{12} possible**

   — many non-pert. uncertainties cancel —

4. **Search for NP in Γ_{12}/M_{12} (and M_{12} - combined analysis)**

Test 1: τ_{B^+}/τ_{B_d} in NLO-QCD I*

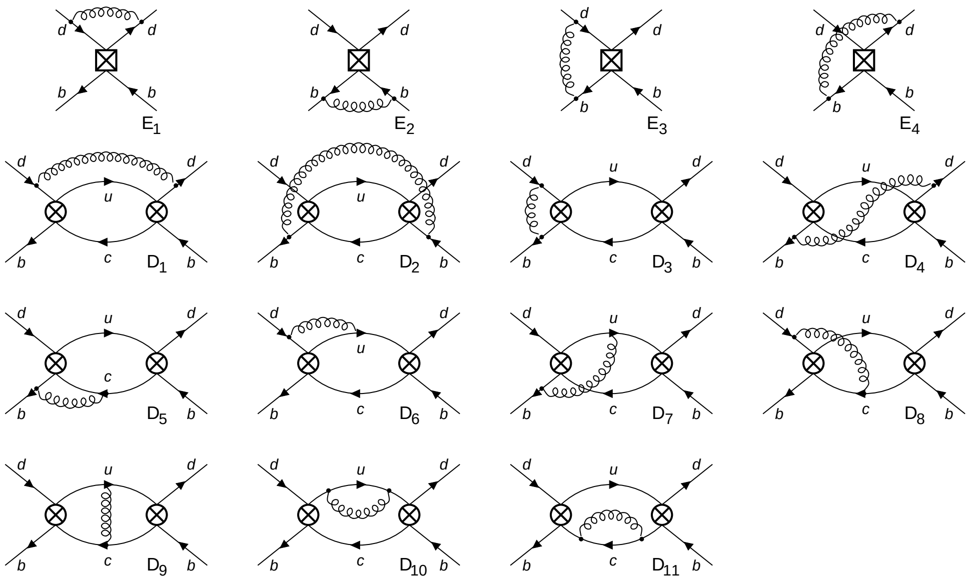
$$\frac{\tau_1}{\tau_2} = 1 + \left(\frac{\Lambda}{m_b}\right)^3 \left(\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{(1)} + ...\right) + \left(\frac{\Lambda}{m_b}\right)^4 \left(\Gamma_4^{(0)} + ...\right) + ...$$

$\Gamma_3^{(0)}$: Shifman, Voloshin; Uraltsev; Bigi, Vainshtein; Neubert, Sachrajda

$\Gamma_4^{(0)}$: Gabbiani, Onishchenko, Petrov; Greub, A.L., Nierste (unpublished)

$\Gamma_3^{(1)}$: Beneke, Buchalla, Greub, A.L., Nierste; Ciuchini,Franco, Lubicz, Mescia, Tarantino

lattice : Di Pierro, Sachrajda, Michael; Becirevic



Test 1: τ_{B^+}/τ_{B_d} in NLO-QCD II*

$$\frac{\tau(B^+)}{\tau(B_d^0)} - 1 = \tau(B^+)\left[\Gamma(B_d^0) - \Gamma(B^+)\right]$$

$$= 0.0325\,\frac{\tau(B^+)}{1.653\,\text{ps}}\left(\frac{|V_{cb}|}{0.04}\right)^2\left(\frac{m_b}{4.8\text{GeV}}\right)^2\left(\frac{f_B}{200\text{MeV}}\right)^2$$

$$\left[(1.0 \pm 0.2)\,B_1 + (0.1 \pm 0.1)\,B_2 - (18.4 \pm 0.9)\,\epsilon_1 + (4.0 \pm 0.2)\,\epsilon_2\right] + \delta_{1/m}$$

$(B_1, B_2, \epsilon_1, \epsilon_2) = (1.10 \pm 0.20,\ 0.99 \pm 0.10,\ -0.02 \pm 0.02,\ 0.03 \pm 0.01)$ '01: Becirevic

$$\left[\frac{\tau(B^+)}{\tau(B_d^0)}\right]_{\text{LO}} = 1.047 \pm 0.049$$

$$\left[\frac{\tau(B^+)}{\tau(B_d^0)}\right]_{\text{NLO}} = 1.063 \pm 0.027$$

NLO-QCD: '02: Beneke, Buchalla, A.L, Greub, Nierste; Ciuchini,Franco, Lubicz, Mescia, Tarantino

$1/m_b$: '03: Gabbiani, Onishchenko, Petrov; Greub, A.L, Nierste (unpublished): tiny ≤ 0.005

HFAG 09: $\left[\frac{\tau(B^+)}{\tau(B_d^0)}\right] = 1.071 \pm 0.009$

Test 2: The lifetime ratio τ_{B_s}/τ_{B_d}*

$$\frac{\tau(B_s)}{\tau(B_d)} = 1.00 \pm 0.01$$

Neubert, Sachrajda; Beneke, Buchalla, Dunietz; Bigi, Blok, Shifman, Uraltsev, Vainshtein; U. Nierste, Y.-Y. Keum; M. Ciuchini, E. Franco, V. Lubicz, F. Mescia

Weak annihilation contributions for B_d and B_s have almost the same size.

Lifetime differences only due to small difference in phase space and by $SU(3)_F$ violations of the hadronic parameters.

NLO penguin contributions to τ_{B_s}/τ_{B_d} give a comparable effect $->$ search for new physics

HFAG 09: $$\left[\frac{\tau(B_s^0)}{\tau(B_d^0)}\right] = 0.965 \pm 0.017$$