SM Predictions on D^0 oscillations and CPV

Alexander Lenz

Technical University of Dortmund and University of Regensburg

in collaboration with

M. Bobrowski, V. Braun, U. Nierste, T. Prill, J. Riedl, J. Rohrwild

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**

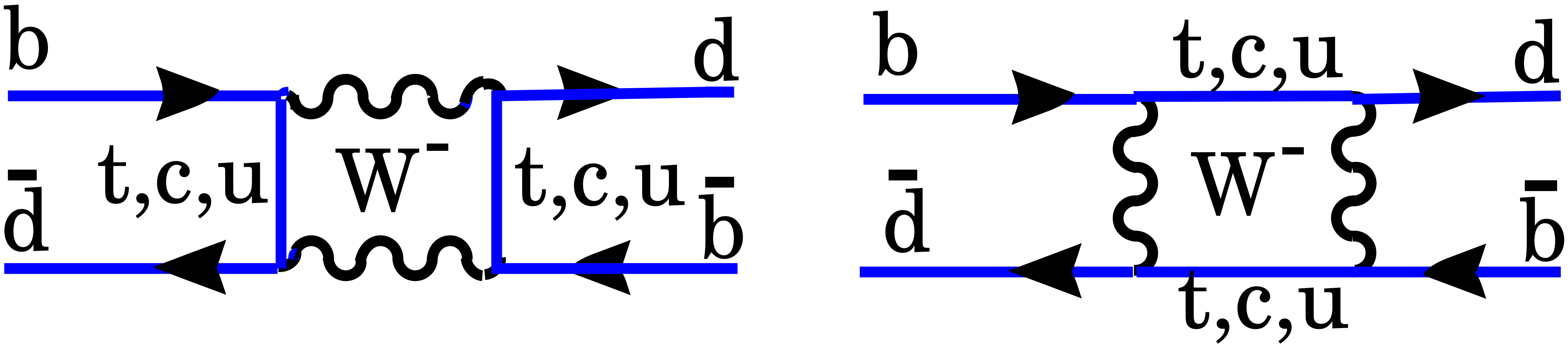
Outlook

Mixing Formalism I

Time evolution of a decaying particle: $B(t) = \exp\left[-i m_B t - \Gamma_B/2 t\right]$
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

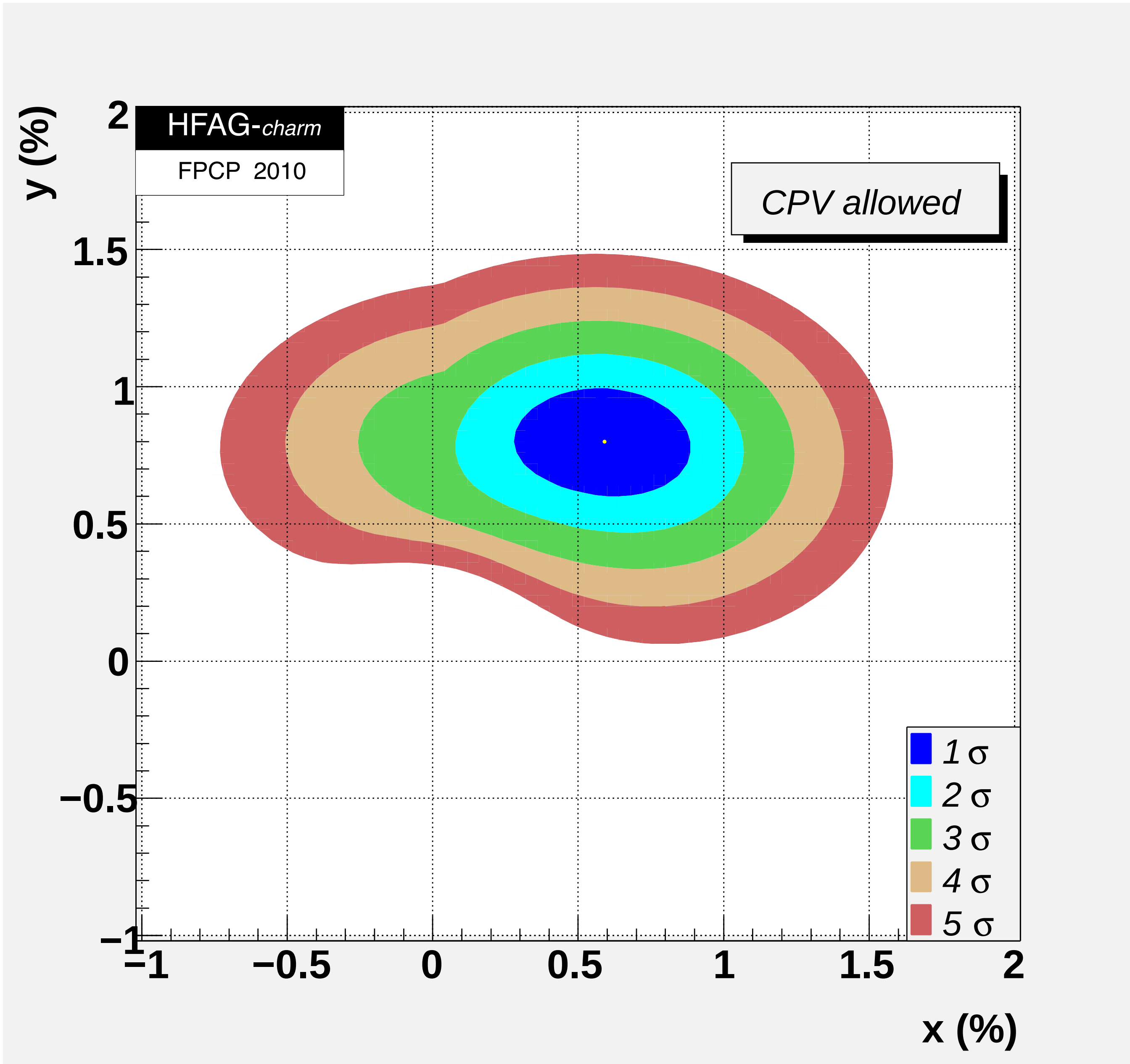
D-mixing is now also experimentally established

	1σ error	95% CL
$x := \frac{\Delta M}{\Gamma}$	$(0.59 \pm 0.20)\ \%$	$[0.19, 0.97]\%$
$y := \frac{\Delta \Gamma}{2\Gamma}$	$(0.83 \pm 0.13)\ \%$	$[0.54, 1.05]\%$

HFAG 2010 (BaBar, Belle, CDF, CLEO)

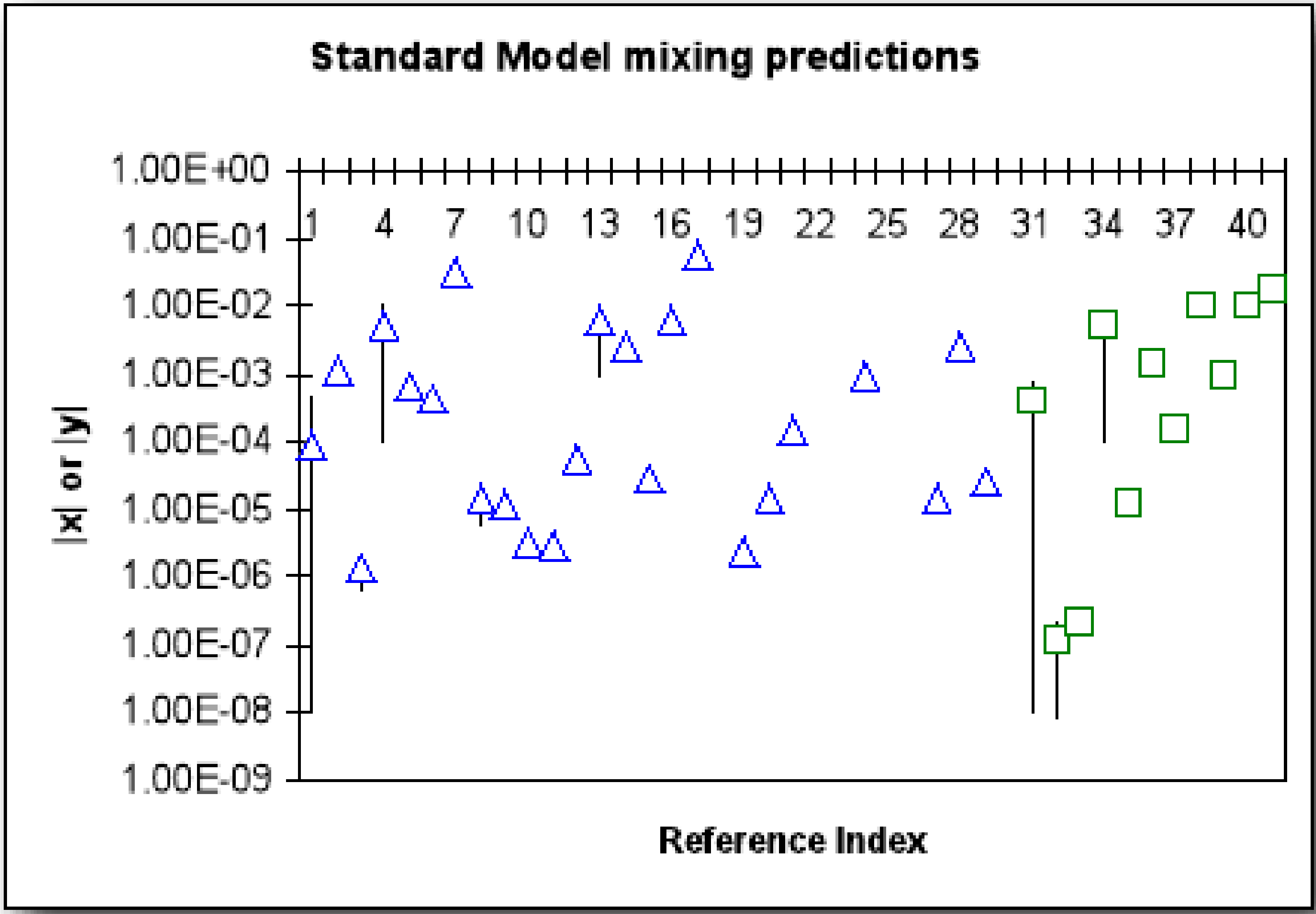
- No single experiment above 5 σ
- David Asner@CKM2010: The more precise, the less significant
- $\Rightarrow \Gamma_{12}/M_{12} \approx \mathcal{O}(1)$, i.e. not so nice formulas as in the B-case

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

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

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

- 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: $(m_b/m_c)^3 \approx 20 \ldots 30$

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

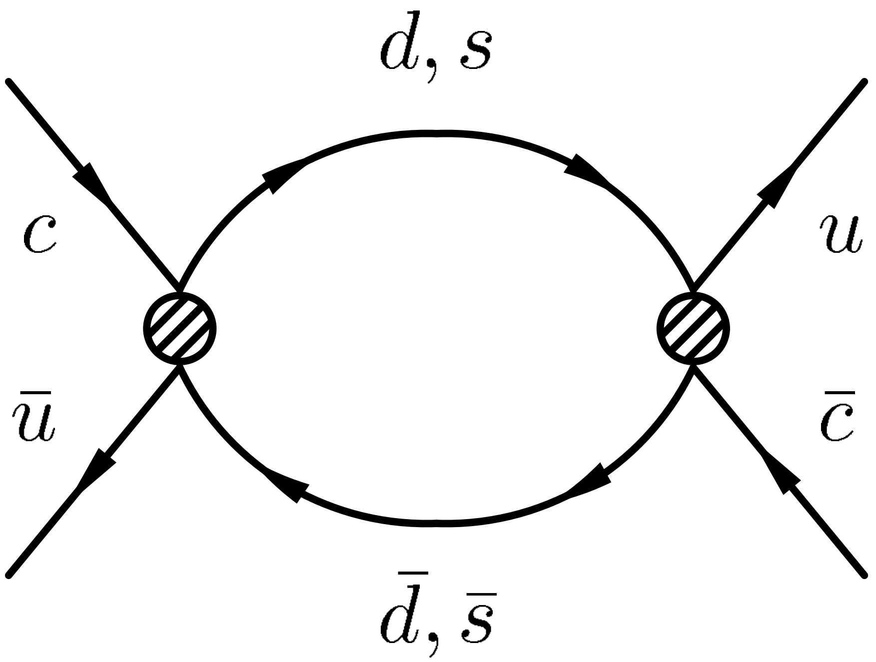
$$\Delta M = 2|M_{12}|\,, \qquad \Delta\Gamma = 2|\Gamma_{12}|\cos\phi\,.$$

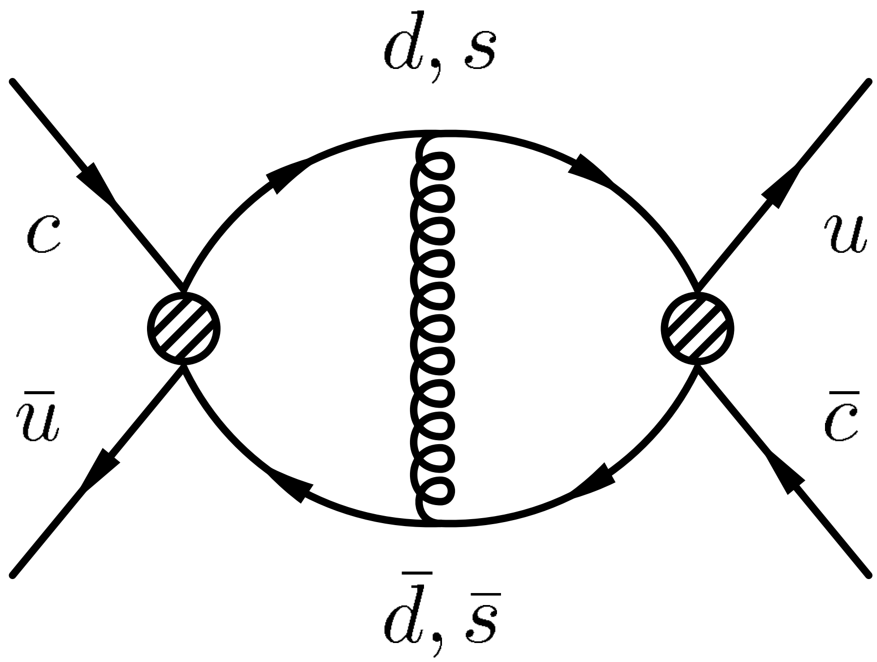
In the D-system $|\Gamma_{12}/M_{12}| \approx 1$ possible — Solve Eigenvalue equation exactly

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**

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

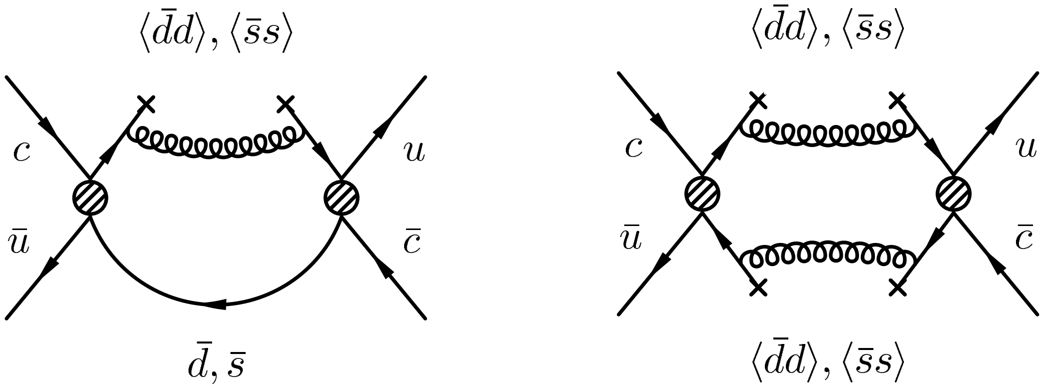
- **Overall result much too small**

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

!!! 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?

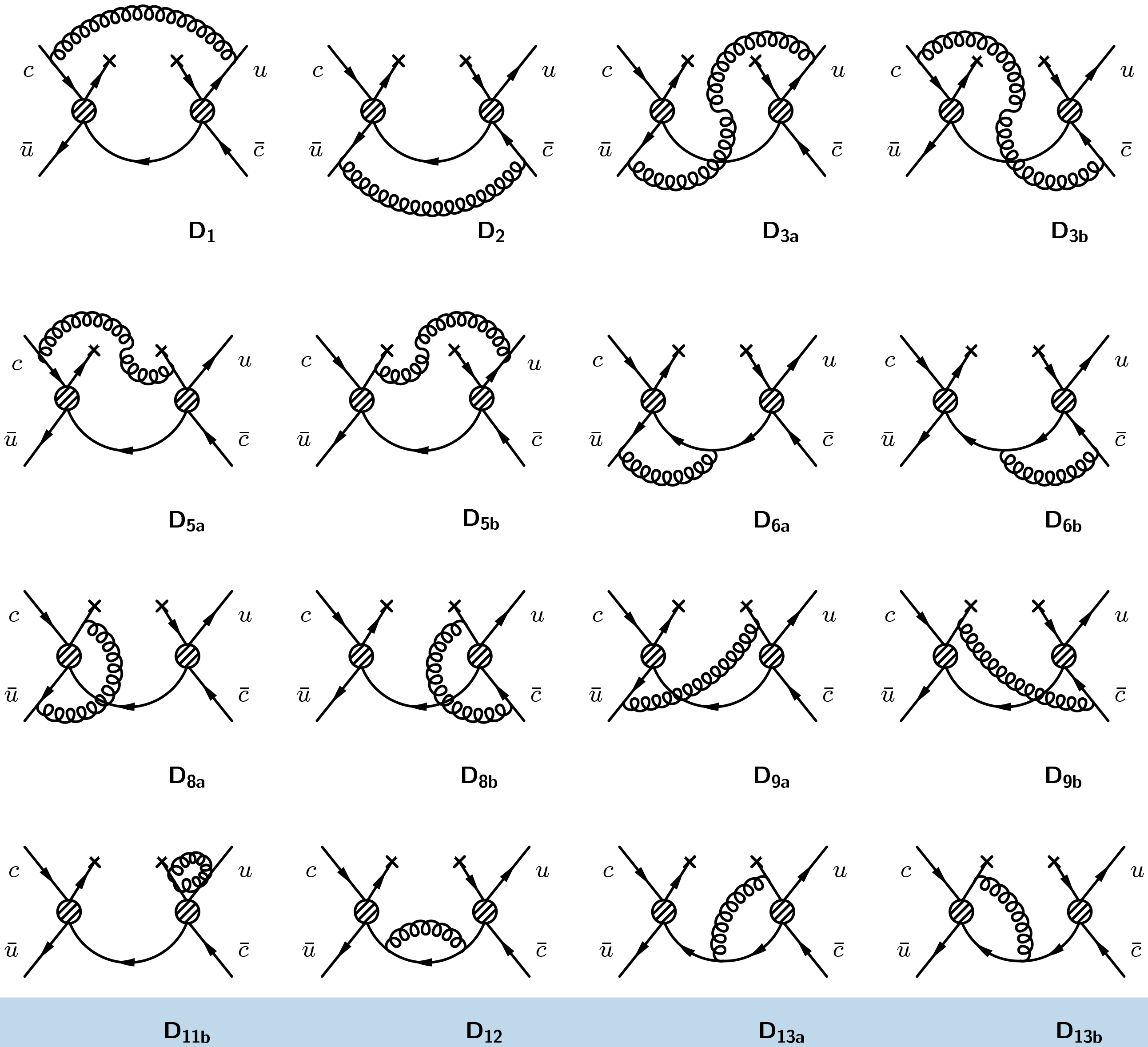
1. Standard argument for "arg Γ_{12} is negligible" is wrong

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

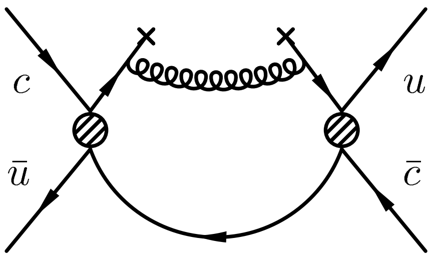
- Factorization approximation, expected to hold up to $1/N_c$
- Enhancement of $\mathcal{O}(15)$ compared to leading term
  Large effect, but not as large as estimated by Bigi, Uraltsev
- GIM cancellation reduced to: $\propto m_s^3$

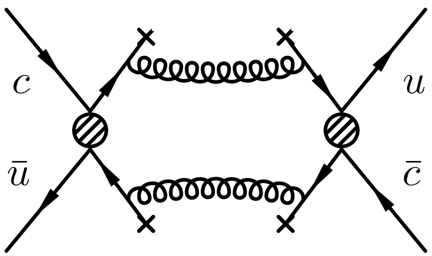
$$\Gamma_{12} \propto \lambda_s^2 \cdot \frac{m_s^6}{m_c^6} + 2\lambda_s\lambda_b \cdot \frac{m_s^2}{m_c^2} + \lambda_b^2 \cdot 1$$

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

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

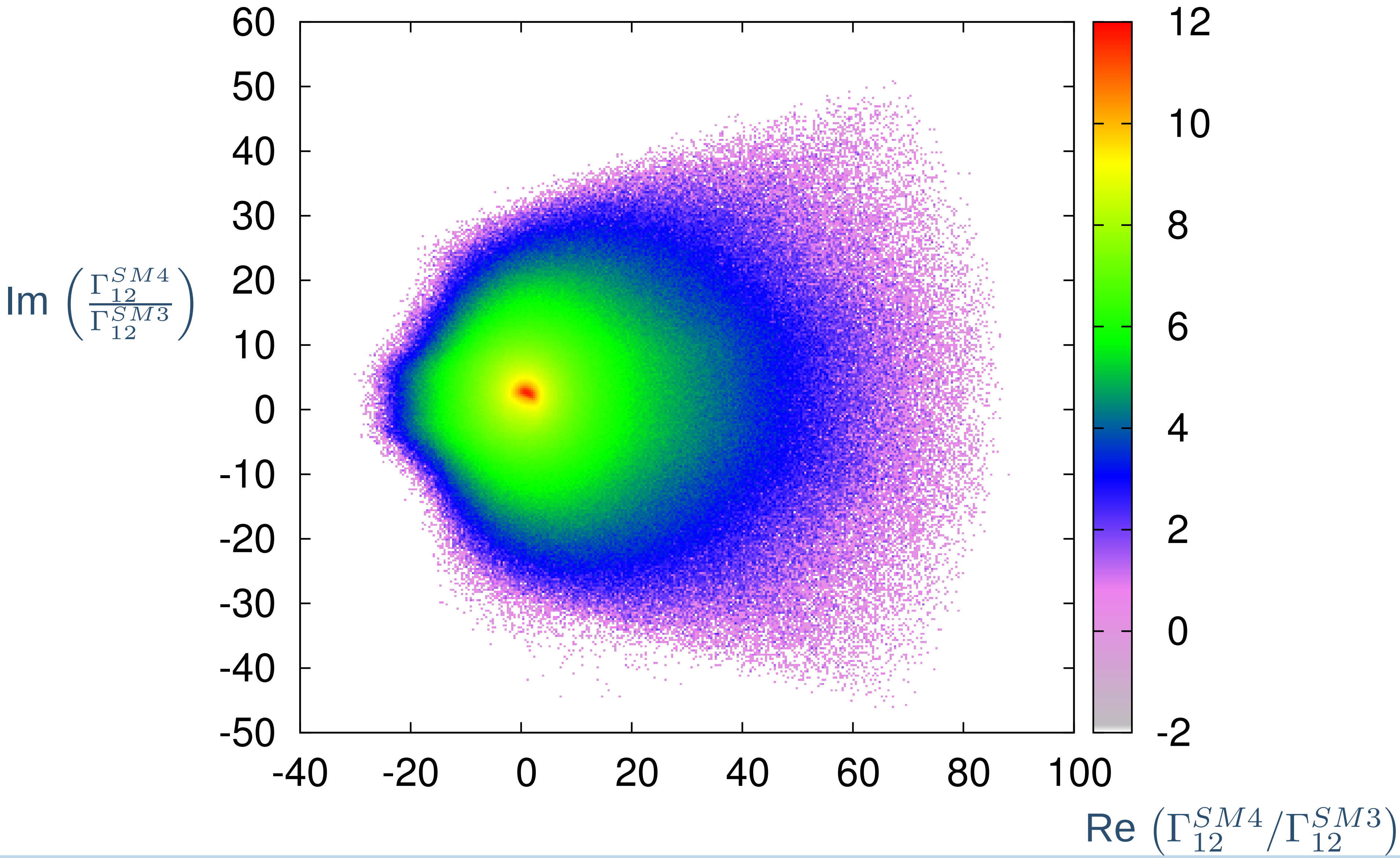
$$\Gamma_{12} = -\lambda_s^2 \left(\Gamma_{ss} - 2\Gamma_{sd} + \Gamma_{dd}\right) + 2\lambda_s(\lambda_b + \lambda_{b'}) \left(\Gamma_{sd} - \Gamma_{dd}\right) - (\lambda_b + \lambda_{b'})^2 \Gamma_{dd}$$

$\lambda_b \propto \lambda^{5\dots6}$ - 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



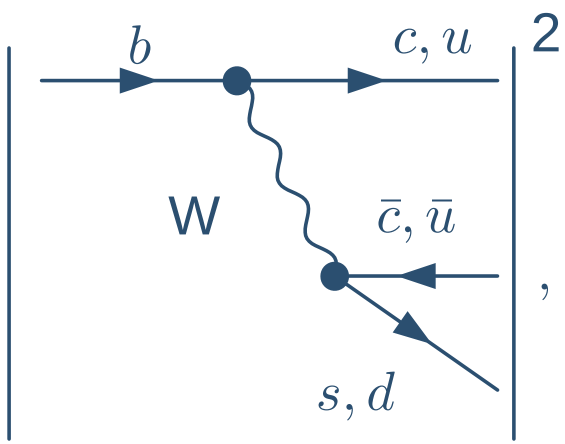
Inclusive Decays I*

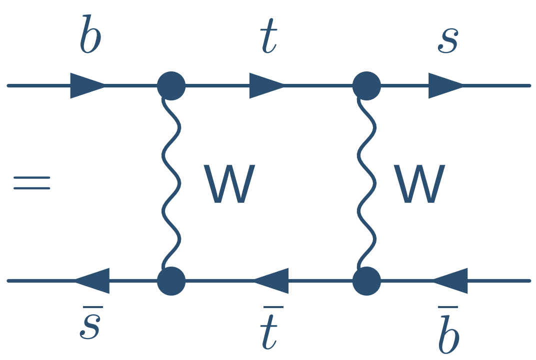
Theoretical determination of observables

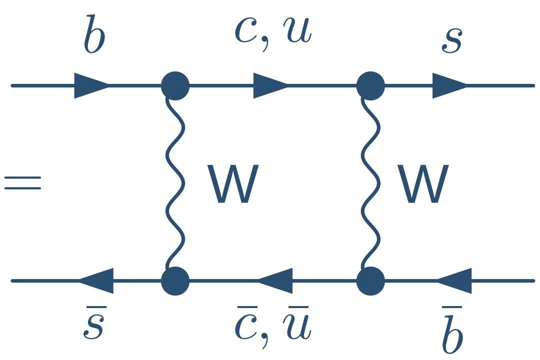
$$\frac{1}{\tau} = \sum_X \Gamma(B \to X)\,, \qquad \Delta M = 2|M_{12}|\,, \qquad \Delta\Gamma = 2|\Gamma_{12}|\cos(\phi)\,,$$

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

These quantities correspond to the following SM diagrams

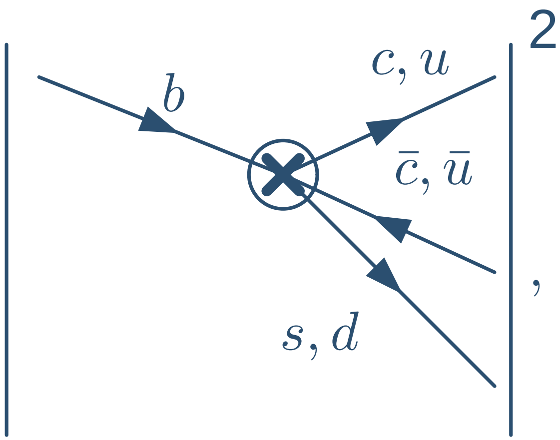
$\Gamma = \int \sum_X$ 

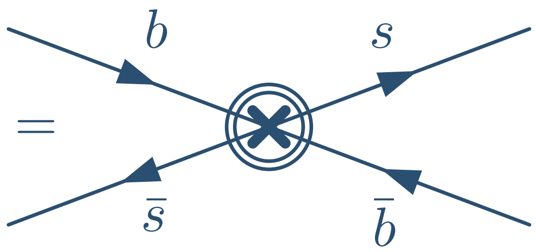
, $M_{12} =$ 

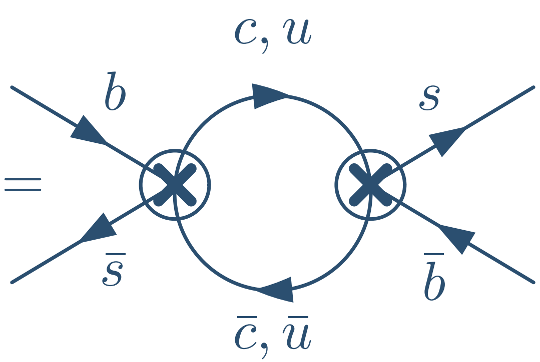
, $\Gamma_{12} =$ 

Inclusive Decays II*

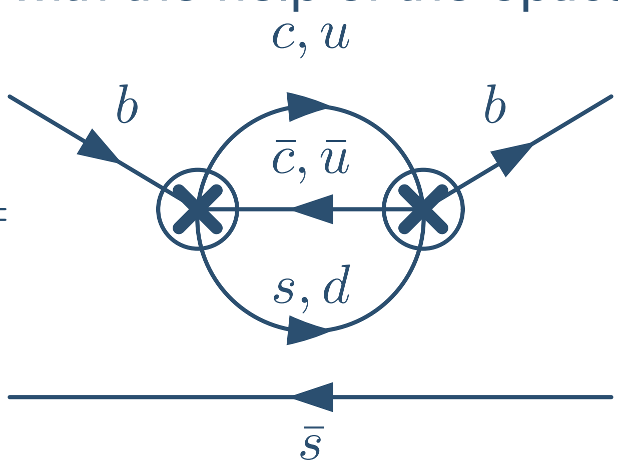
Use the fact: $m_t, M_W \gg m_b$ - integrate out heavy particles

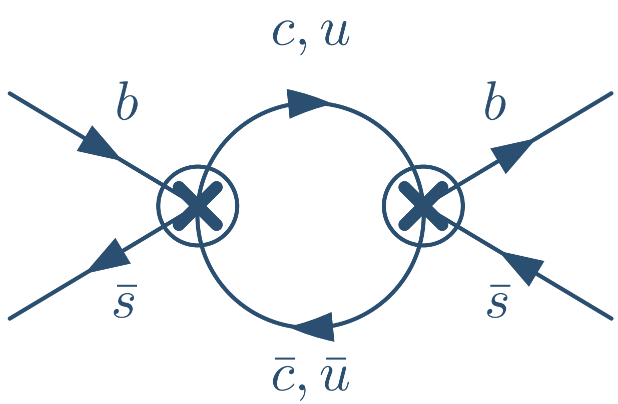
$\Gamma = \int \sum_X$ 

, $M_{12} =$ 

, $\Gamma_{12} =$ 

Rewrite Γ with the help of the optical theorem

$\Gamma =$ 

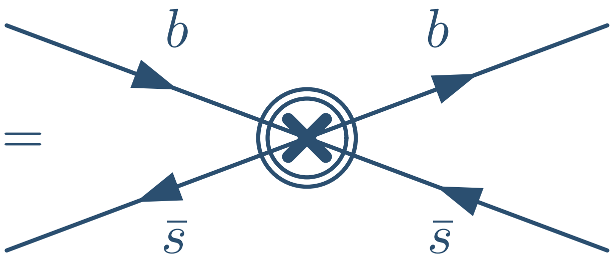
$+ \dots +$ 

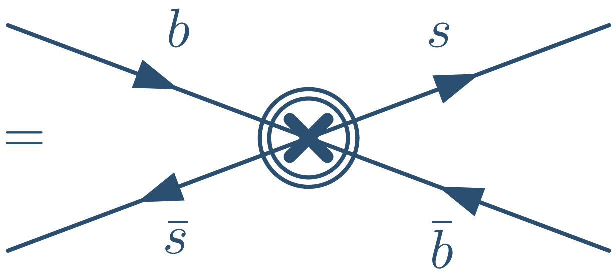
$+ \dots$

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

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

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

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

Baryon vs Meson

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

Neutral Mesons

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

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

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*

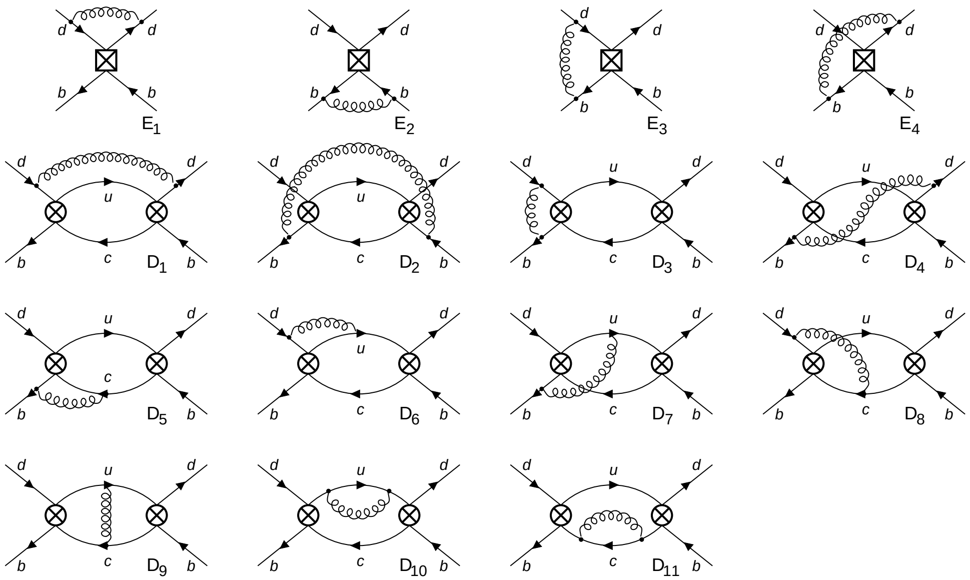
$$\frac{\tau_1}{\tau_2} = 1 + \left(\frac{\Lambda}{m_b}\right)^3 \left(\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{(1)} + ...\right) + \left(\frac{\Lambda}{m_b}\right)^4 \left(\Gamma_4^{(0)} + ...\right) + ...$$

$\Gamma_3^{(0)}$: 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*

$$
\begin{aligned}
\frac{\tau(B^+)}{\tau(B_d^0)} - 1 \;&=\; \tau(B^+)\,\left[\Gamma(B_d^0) - \Gamma(B^+)\right] \\
&=\; 0.0325\, \frac{\tau(B^+)}{1.653\,\text{ps}} \left(\frac{|V_{cb}|}{0.04}\right)^2 \left(\frac{m_b}{4.8\text{GeV}}\right)^2 \left(\frac{f_B}{200\text{MeV}}\right)^2 \\
&\quad \left[(1.0 \pm 0.2)\, B_1 \;+\; (0.1 \pm 0.1)\, B_2 \;-\; (18.4 \pm 0.9)\, \epsilon_1 \;+\; (4.0 \pm 0.2)\, \epsilon_2\right] + \delta_{1/m}
\end{aligned}
$$

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

$$\left[\frac{\tau(B^+)}{\tau(B_d^0)}\right]_{\text{LO}} \;=\; 1.047 \pm 0.049 \qquad \left[\frac{\tau(B^+)}{\tau(B_d^0)}\right]_{\text{NLO}} \;=\; 1.063 \pm 0.027$$

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

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

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

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

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

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