B_s mixing

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Outline

Introduction: B mixing

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- Heavy Quark Expansion
- State of the art
- Strategy

Lifetimes - Test HQE

- τ_{B_+}/τ_{B_d}
- τ_{B_s}/τ_{B_d}
- $\tau_{\Lambda_b}/\tau_{B_d}$
- $\tau_{\Xi_b^0}/\tau_{\Xi_b^+}$
- τ_{B_c}
- Lessons from lifetimes

SM predictions for $B_q - \bar{B}_q$-mixing

- ΔM
- Non-perturbative parameters
- $\Delta\Gamma$ and $\Delta\Gamma/\Delta M$
- a_{fs} or ϕ

Search for NP in $B_q - \bar{B}_q$-mixing

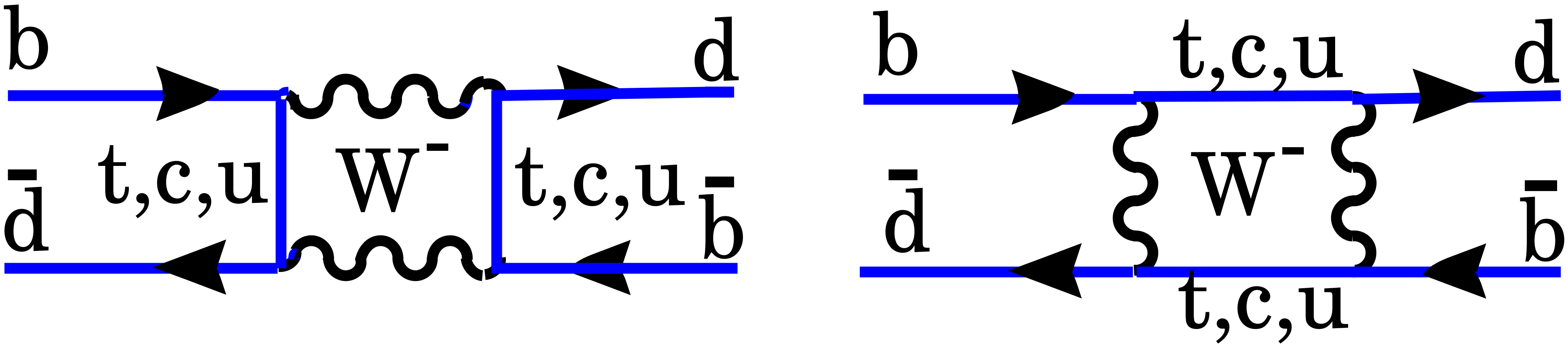
- General Strategy
- Current experimental bounds
- Some models

Outlook

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 $B_{d,s} \rightarrow \bar{B}_{d,s}$ 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

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

B-mixing II

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

- **Mass difference:** $\Delta M := M_H - M_L = 2|M_{12}| \left(1 + \frac{1}{8}\frac{|\Gamma_{12}|^2}{|M_{12}|^2}\sin^2\phi + \ldots\right)$
  $|M_{12}|$: heavy internal particles: t, SUSY, ...
- **Decay rate difference:** $\Delta\Gamma := \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos\phi \left(1 - \frac{1}{8}\frac{|\Gamma_{12}|^2}{|M_{12}|^2}\sin^2\phi + \ldots\right)$
  $|\Gamma_{12}|$: light internal particles: u, c, ... (almost) no NP!!!
- **Flavor specific/semileptonic CP asymmetries:** ??? Studies at ATLAS, CMS ???
  $\bar{B}_q \to f$ 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*)

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

Theoretical framework - SM

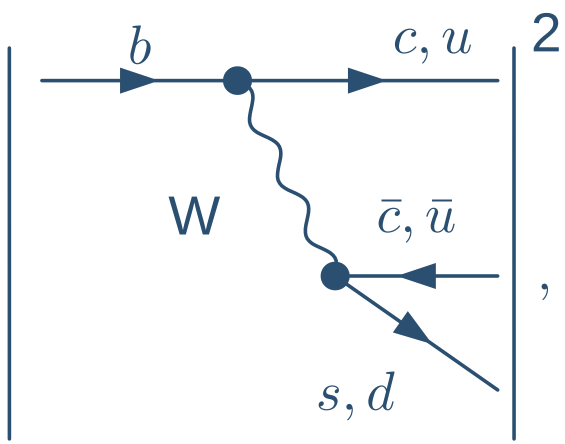
Theoretical determination of observables

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

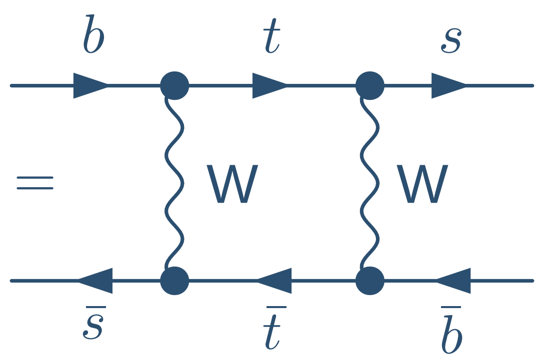
$$a_{sl} = \Im\left(\frac{\Gamma_{12}}{M_{12}}\right)\,, \qquad \phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)\,.$$

These quantities correspond to the following SM diagrams

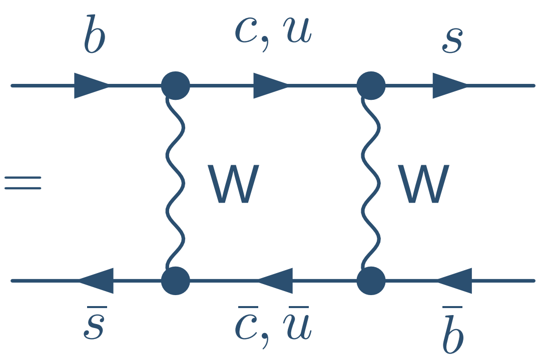
$\Gamma = \int \sum_X$



, $M_{12} =$

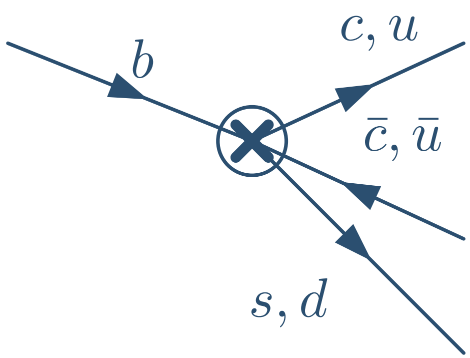
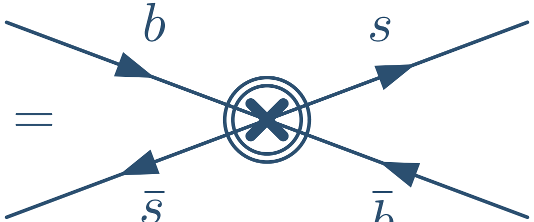
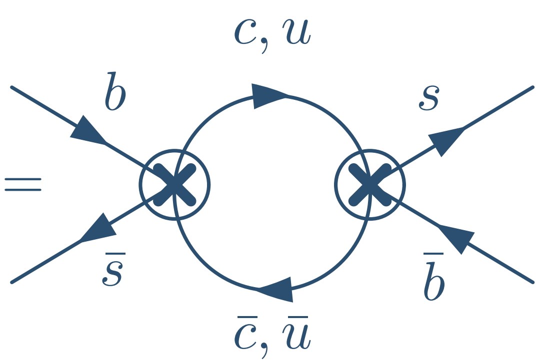


, $\Gamma_{12} =$

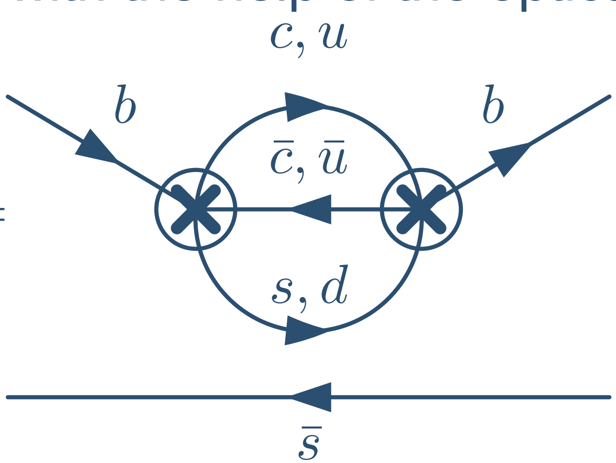
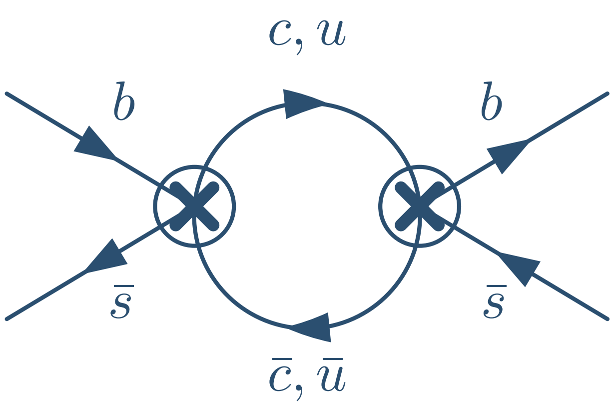


Theoretical framework - OPE I

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

$\Gamma = \int \sum_X \Bigg|$  $\Bigg|^2$, $M_{12} =$  , $\Gamma_{12} =$ 

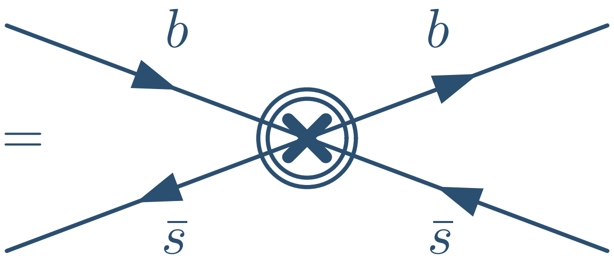
Rewrite Γ with the help of the optical theorem

$\Gamma =$  $+ \ldots +$  $+ \ldots$

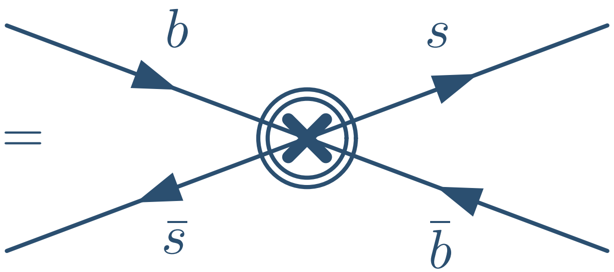
Γ_0 Γ_3

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 - see talk by Ikaros Bigi**

$\Rightarrow$ **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. **Clean SM prediction of Γ_{12}/M_{12} possible**

   — many non-pert. uncertainties cancel —

4. **Search for NP in Γ_{12}/M_{12}**

τ_{B^+}/τ_{B_d} in NLO-QCD I

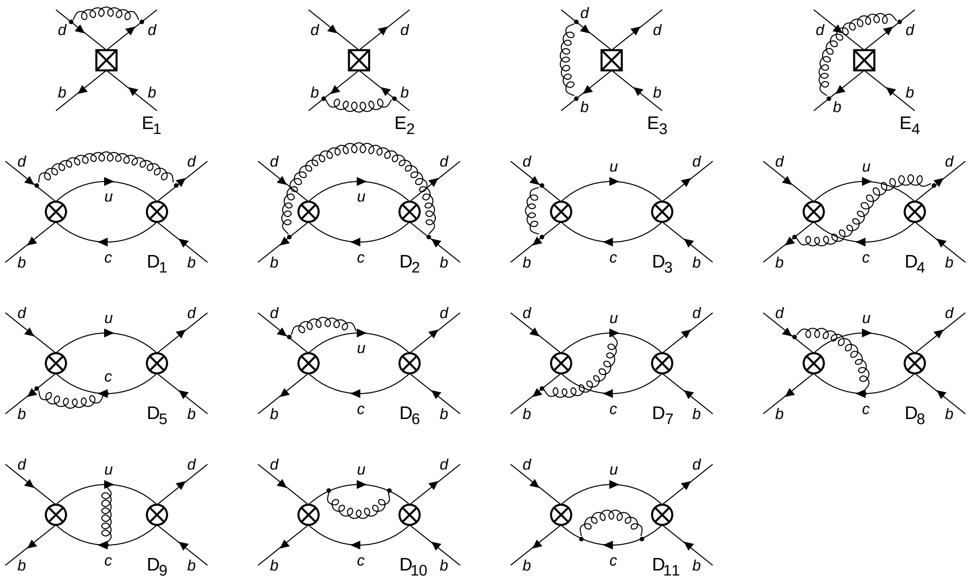
$$\frac{\tau_1}{\tau_2} = 1 + \left(\frac{\Lambda}{m_b}\right)^3 \left(\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{(1)} + ...\right) + \left(\frac{\Lambda}{m_b}\right)^4 \left(\Gamma_4^{(0)} + ...\right) + ...$$

$\Gamma_3^{(0)}$: 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



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

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

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

HFAG 08: $\left[\frac{\tau(B^+)}{\tau(B_d^0)}\right] = 1.071 \pm 0.009$

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 08: $\left[\frac{\tau(B_s^0)}{\tau(B_d^0)}\right] = 0.961 \pm 0.018$

The lifetime ratio $\tau_{\Lambda_b}/\tau_{B_d}$

Be careful!

Theoretically in a much worse shape than τ_{B+}/τ_{B_d}

- NLO-QCD incomplete
- Only preliminary lattice studies for the Λ_b matrix elements available (di Pierro, Sachrajda)
- Certain Penguin contractions on the lattice are missing

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} = 0.88 \pm 0.05$$

C. Tarantino, hep-ph/0702235; E. Franco, V. Lubicz, F. Mescia, C.Tarantino; F. Gabbiani, A. Onishchenko, A. Petrov

HFAG 08: $\left[\frac{\tau(\Lambda_b)}{\tau(B_d^0)}\right] = 0.904 \pm 0.032$ CDF vs D0!!!

Lifetime ratios of the Ξ_b-baryons

Here the problematic penguin contributions cancel
$\Rightarrow$ in principle: clear determination possible
$\Rightarrow$ in practice: no determination of non-pert. ME avaiable

$$\frac{1}{\bar{\tau}(\Xi_b)} = \bar{\Gamma}(\Xi_b) = \Gamma(\Xi_b) - \Gamma(\Xi_b \to \Lambda_b + X)\,.$$

Using the preliminary lattice values for Λ_b

$$\frac{\bar{\tau}(\Xi_b^0)}{\bar{\tau}(\Xi_b^+)} = 1 - 0.12 \pm 0.02 \pm ???\,,$$

$???$: unknown systematic errors.

$\bar{\tau}(\Xi_b^0) \approx \tau(\Lambda_b)$ - similar to τ_{B_s}/τ_{B_d} -

$$\frac{\tau(\Lambda_b)}{\bar{\tau}(\Xi_b^+)} = 0.88 \pm 0.02 \pm ???\,.$$

Lifetime of the double-heavy meson $\tau_{B_c^+}$

LO analysis gives

$$\tau(B_c) = 0.4 \ldots 0.7 \text{ ps} \quad \text{vs.} \quad \tau(B_c) = 0.48 \pm 0.05 \text{ ps}$$

Beneke, Buchalla;

Bigi; Colangelo et al.; Anisimov et al.; Lusignoli, Masetti; Quigg; Kiselev et al; Chang et al.

Data: HFAG 08

$$\tau(B_c) = 0.463 \pm 0.071 \text{ ps}$$

Lessons from lifetimes

1. Test reliability of the theoretical framework via lifetimes
   — no NP effects expected —
   - $\tau(B^+)/\tau(B_d)$: HQE in perfect shape
   - $\tau(B_s)/\tau(B_d)$: More data desireable
   - $\tau(\Lambda_b)$, $\tau(\Xi_b)$ and $\tau(B_c)$: more theoretical work and more data needed
2. Currently no precise prediction of Γ_{12} and M_{12} possible
   — compared to $\Delta M^{\text{Exp.}}$ —
3. Clean SM prediction of Γ_{12}/M_{12} possible
   — many non-pert. uncertainties cancel —
4. Search for NP in Γ_{12}/M_{12}

The mass difference ΔM

Calculating the Boxdiagram with an internal top-quark yields

$$M_{12,q} = \frac{G_F^2}{12\pi^2}(V_{tq}^* V_{tb})^2 M_W^2 S_o(x_t) B_{B_q} f_{B_q}^2 M_{B_q} \hat{\eta}_B$$

(Inami, Lim '81)

- Hadronic matrix element: $\frac{8}{3} B_{B_q} f_{B_q}^2 M_{B_q} = \langle \bar{B}_q | (\bar{b}q)_{V-A} (\bar{b}q)_{V-A} | B_q \rangle$
- Perturbative QCD corrections $\hat{\eta}_B$ (Buras, Jamin, Weisz, '90)

$\Delta M_s = 19.3 \pm 6.7\,\text{ps}^{-1}$ better: $\frac{\Delta M_s}{\Delta M_d} = \frac{M_{B_s}}{M_{B_d}} \left| \frac{V_{ts}^2}{V_{td}^2} \right| \frac{f_{B_s}^2 B_{B_s}}{f_{B_d}^2 B_{B_d}}$

Experimental status: Heavy Flavor Averaging Group, 08

$$\Delta M_d = 0.507 \pm 0.005\ ps^{-1}$$

ALEPH, CDF, D0, DELPHI, L3, OPAL, BABAR, BELLE, ARGUS, CLEO

$$\Delta M_s = 17.77 \pm 0.10(stat) \pm 0.07(syst)\ ps^{-1}$$

CDF hep-ex/0609040, D0 5474 (18.56 ± 0.87)

Important bounds on the unitarity triangle and new physics

Non-perturbative Parameters I: f_{B_s} - the easiest

Sum rules, quark model

- **2002: Jamin, Lange,** 244 ± 21 **MeV**
- **2004: Cvetic et al,** 216 ± 32 **MeV**
- **2006: Ebert et al,** 218 **MeV**
- **2007: Badalion, Simonov** 222 **MeV**
- **2007: Choi,** 234 **MeV**

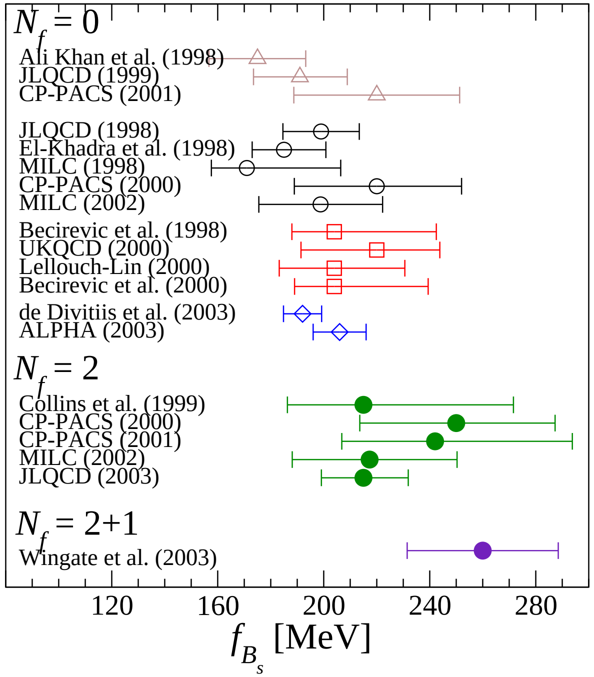
Lattice quenched

- **2000: Becirevic et al,** 204^{+17}_{-15} **MeV**
- **2003: ALPHA,** 205 ± 12 **MeV**
- **2006: Sommer et al,** 191 ± 6 **MeV**
- **2007: Ali Khan et al,** 205 ± 32 **MeV**
- **2007: TWQCD,** 253 ± 11 **MeV**

Lattice unquenched, $n_f = 2$

- **1999: Collins et al,** 212^{+64}_{-29} **MeV**
- **2000: CP-PACS,** 250^{+37}_{-36} **MeV**
- **2001: CP-PACS,** 242^{+52}_{-35} **MeV**
- **2002: MILC,** 217^{+34}_{-22} **MeV**
- **2003: JLQCD,** 216^{+31}_{-28} **MeV**
- **2004: UKQCD,** 256 ± 45 **MeV**

- **2005: Gadiyak, Loktik** 341 ± 32 **MeV**
- **2005: Della Morte et al** 297 ± 14 **MeV**



Hashimoto

hep-ph/0411126

Lattice unquenched, $n_f = 2 + 1$

- **2003: Wingate et al,** 260 ± 29 **MeV**
- **2005: HP QCD,** 259 ± 32 **MeV**
- **2007: Fermilab,** 274 ± 32 **MeV**

The decay constant problem

I) Taking published lattice errors literally (e.g. talk from A. Kronfeld)

f_{B_s}	N_F	ΔM_s	deviation from experiment
193 ± 06 MeV	0	12.5 ± 1.4 ps^{-1}	$-3.9\ \sigma$
205 ± 32 MeV	2	14.1 ± 4.6 ps^{-1}	$-0.8\ \sigma$
259 ± 26 MeV	3	22.5 ± 5.0 ps^{-1}	$+0.9\ \sigma$
297 ± 14 MeV	2	30.0 ± 3.9 ps^{-1}	$+3.1\ \sigma$
341 ± 32 MeV	2	39.0 ± 8.2 ps^{-1}	$+2.6\ \sigma$

II) Try to be conservative

Look also at other non-pert. methods, e.g. sum rules -
10 to 20 $\%$ uncertainty expected — see also historic review of Melikhov

we use: $f_{B_s} \quad = \quad 240 \pm 40$ MeV

- No precission determination of ΔM and $\Delta \Gamma$ possible
- In Γ_{12}/M_{12} the decay constant cancels

Non perturbative Parameters II

$$\langle \bar{B}_s | (\bar{s}b)_{V-A} (\bar{s}b)_{V-A} | B_s \rangle \quad = \quad \frac{8}{3} M_{B_s} f_{B_s}^2 B \, , \, ...$$

- B, B_S with $n_f = 2$ from JLQCD,01 & 03
- until 2006: only 1 published determination of $\tilde{B}_S$: Becirevic et al. 01
- B, B_S and $\tilde{B}_S$ with $n_f = 2+1$, staggered (HPQCD 06, Fermilab, MILC 07): Combined determination of $f_{B_s}\sqrt{B_x} \Rightarrow$ smaller error

f_{B_d} - extrapolation to small quark masses: e.g. HPQCD ($n_f = 2+1$) vs. Belle

$$f_{B_d} \quad = \quad (216 \pm 22) \text{ MeV vs. } \left(229^{+47}_{-46}\right) \text{ MeV}$$

Clean ratio? $\xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}} = 1.2...1.3$ (e.g. Della Morte, Lattice 07)

Γ_{12} in NLO-QCD

$$\Gamma_{12} = \left(\frac{\Lambda}{m_b}\right)^3 \left(\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{(1)} + ...\right) + \left(\frac{\Lambda}{m_b}\right)^4 \left(\Gamma_4^{(0)} + ...\right) + ...$$

$\Gamma_3^{(0)}$	:	Hagelin; Buras, Slominski, Steger; Datta, Paschos, Türke,Wu;
		Voloshin, Uraltsev, Khoze, Shifman; Chau; Franco,Lusignoli, Pugliese; (1981 . . .)
$\Gamma_3^{(1)}$	:	Beneke, Buchalla, Greub, A.L., Nierste (1998,2003)
		Ciuchini, Franco, Lubicz, Mescia, Tarantino (2003)
$\langle\vert\vert\rangle$	:	HPQCD, JLQCD, Becirevic et al.; Gimenez, Reyes; Jamin, Lange
		Huang, Zhang, Zhou; Blossier; Detmold, Lin... (1999 . . .)
$\Gamma_4^{(0)}$	:	Beneke, Buchalla, Dunietz (1996); Dighe, Hurth, Kim, Yoshikawa (2001)
$\Gamma_5^{(0)}$	:	A.L., Nierste (2006), Badin, Gabbiani, Petrov (2007)
$\langle\vert\vert\rangle$	:	part of operators of dim 7 and 8 Becirevic et al (2001), Mannel et al (2007)

New determination of Γ_{12}: A.L., Nierste, 2006

- In the calculation of Γ_{12} 4 operators arise: $Q, Q_S, \tilde{Q}, \tilde{Q}_S$ **hep-ph/0612167, JHEP**
- They are not independent: $(\alpha_i = 1 + \mathcal{O}(\alpha_s))$

$$\tilde{Q} = Q \quad \text{and} \quad R_0 = Q_S + \alpha_1 \tilde{Q}_S + \frac{\alpha_2}{2} Q = \mathcal{O}\left(\frac{1}{m_b}\right)$$

- Old Basis: $\{Q, Q_S\} \Longleftrightarrow$ New Basis $\{Q, \tilde{Q}_S\}$

Problems in the old basis: A.L. hep-ph/0412007

:-(Almost complete cancellation in coefficient of Q

:-(Huge $1/m_b$-corrections

:-(Large α_s-corrections

Γ_{12}^{new}:

+ New basis free of the above shortcomings
+ Use also $\overline{MS}$-scheme for m_b
+ Sum $z \ln z$ to all orders
+ Include subleading CKM structures

$\Delta\Gamma_s$ and $\Delta\Gamma_s/\Delta M_s$

Old basis and pole scheme of m_b

$$\Delta\Gamma_s = \left(\frac{f_{B_s}}{240\,\text{MeV}}\right)^2 \left[0.002 B + 0.094 B'_S - \left(0.033 B_{\tilde{R}_2} + 0.019 B_{R_0} + 0.005 B_R\right)\right]$$

$$\frac{\Delta\Gamma_s}{\Delta M_s} = 10^{-4} \cdot \left[0.9 + 40.9 \frac{B'_S}{B} - \left(14.4 \frac{B_{\tilde{R}_2}}{B} + 8.5 \frac{B_{R_0}}{B} + 2.1 \frac{B_R}{B}\right)\right]$$

New basis, sum up $z \ln z$, average of pole and $\overline{\text{MS}}$-scheme for m_b

$$\Delta\Gamma_s = \left(\frac{f_{B_s}}{240\,\text{MeV}}\right)^2 \left[0.105 B + 0.024 \tilde{B}'_S - \left(0.030 B_{\tilde{R}_2} - 0.006 B_{R_0} + 0.003 B_R\right)\right]$$

$$\frac{\Delta\Gamma_s}{\Delta M_s} = 10^{-4} \cdot \left[46.2 + 10.6 \frac{\tilde{B}'_S}{B} - \left(13.2 \frac{B_{\tilde{R}_2}}{B} - 2.5 \frac{B_{R_0}}{B} + 1.2 \frac{B_R}{B}\right)\right]$$

Now a precise determination of $\Delta\Gamma/\Delta M$ is possible!

Why to prefer one basis?

- Γ_{12}/M_{12}: **obvious**
  In the new basis the dominant part has **no non-perturbative contributions**!!!

- Γ_{12}: **less obvious**
  $\Rightarrow$ one might think to average over the two bases
  this already reduces the uncertainties considerably

  BUT, this is a bad idea
  - Smallness of $1/m_b$ corrections holds to all orders in QCD (Coefficient of R_0 is color-supressed in the new basis)
  - Correlation between Q, Q_S and $\tilde{Q}_S$ is not taken fully into account in the old basis, large cancellations occurs
  $$\tilde{B}_s - 5B_S + 4B = \mathcal{O}(\Lambda/m_b, \alpha_s)$$

$\Rightarrow$ We strongly suggest to use only the new basis!!!

$\Delta\Gamma_s$ and $\Delta\Gamma_s/\Delta M_s$

Old basis and assume no new physics in B_s-mixing ($\equiv f_{B_s} = 230$ MeV)

$$\frac{\Delta\Gamma_s}{\Gamma_s} = \left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^{Theory} \cdot \Delta M_s^{Exp} \cdot \tau_B^{Exp} = 0.10 \pm 0.06$$

(= Bona et al, hep-ph/0605213;)

New basis:

$$\Delta\Gamma_s = (0.096 \pm 0.039)\ \text{ps}^{-1} \quad \Rightarrow \quad \frac{\Delta\Gamma_s}{\Gamma_s} = 0.147 \pm 0.060$$

$$\frac{\Delta\Gamma_s}{\Delta M_s} = (49.7 \pm 9.4) \cdot 10^{-4} \quad \Rightarrow \quad \frac{\Delta\Gamma_s}{\Gamma_s} = 0.127 \pm 0.024$$

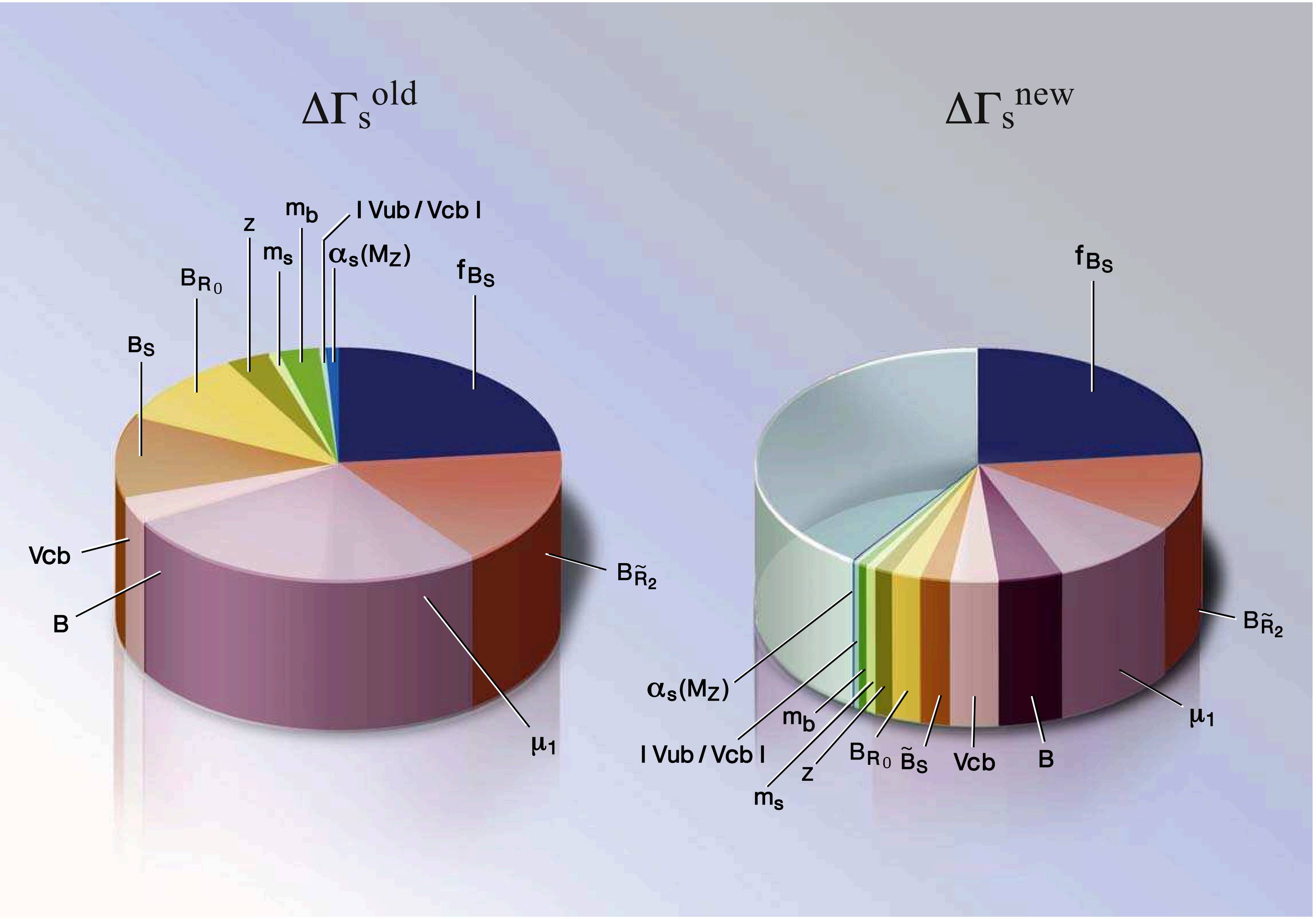
Experiment: HFAG 08 vs. D0 arXiv:0802.2255 vs. CDF arXiv:0712.2397

$$|\Delta\Gamma_s| = (0.088 \pm 0.048)\ \text{ps}^{-1} \quad \text{vs.} \quad (0.19 \pm 0.07)\ \text{ps}^{-1} \quad \text{vs.} \quad < (0.4\,\text{ps}^{-1})^*$$

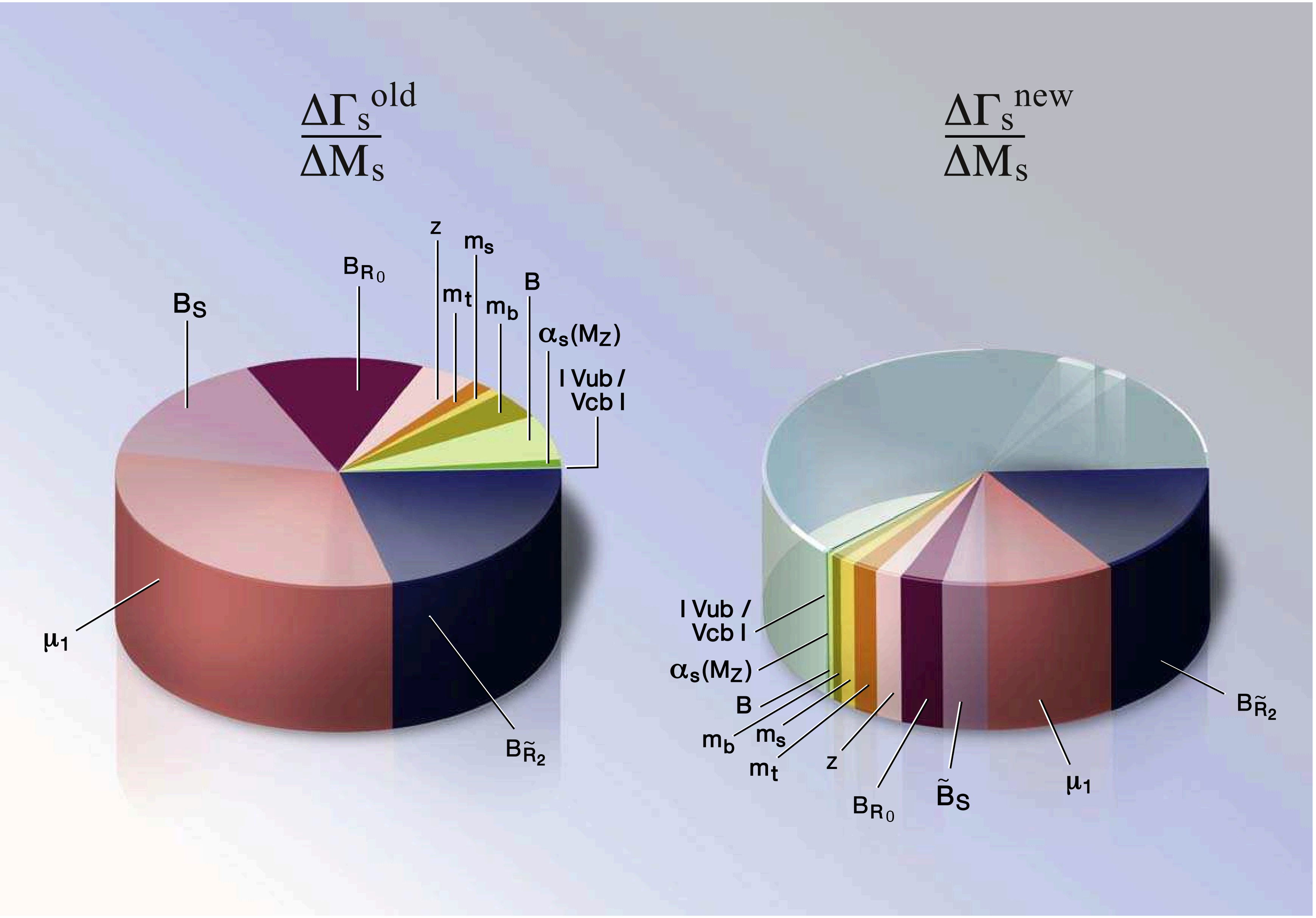
$$\left|\frac{\Delta\Gamma_s}{\Delta M_s}\right| = (50 \pm 27) \cdot 10^{-4} \quad \text{vs.} \quad (73 \pm 51) \cdot 10^{-4} \quad \text{vs.} \quad < (225 \cdot 10^{-4})^*$$

*: depends on Φ_s

Error budget for $\Delta\Gamma_s$



Error budget for $\Delta\Gamma_s/\Delta M_s$



Semileptonic CP-asymmetries a_{fs} and $\Delta\Gamma_d$

SM expectations: A.L., U. Nierste, hep-ph/0612167

$$\begin{aligned} a_{fs}^s &= (2.06 \pm 0.57) \cdot 10^{-5} \\ \phi_s &= 0.24^\circ \pm 0.08^\circ \\ a_{fs}^d &= -(4.8 \pm 1.1) \cdot 10^{-4} \\ \frac{\Delta\Gamma_d}{\Gamma_d} &= (4.1 \pm 1.0) \cdot 10^{-3} \end{aligned}$$

Experimental bounds

$$a_{fs}^s = -(30 \pm 1010) \cdot 10^{-5}$$ (HFAG 08)

$$\phi_s = -39.8^\circ \pm 11.2^\circ$$ (UT-Fit, arXiv:0803.0659)

$$a_{fs}^d = -(5 \pm 56) \cdot 10^{-4}$$ (HFAG 08)

$$\frac{\Delta\Gamma_d}{\Gamma_d} = (9 \pm 37) \cdot 10^{-3}$$ (HFAG 08)

typical enhancement due to NP: $a_{fs}^s \approx 500 \cdot 10^{-5}$ close to exp. error!

New physics in B-mixing I

There is still plenty of room for a “pinch “ of new physics in B-mixing

New physics in mixing II

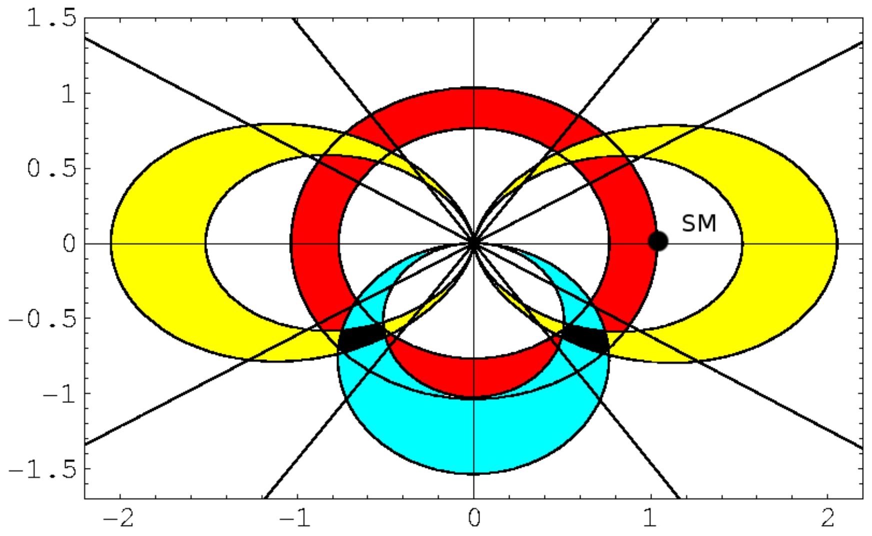
$$\Gamma_{12,s} = \Gamma_{12,s}^{\rm SM}\,, \qquad M_{12,s} = M_{12,s}^{\rm SM} \cdot \Delta_s\,; \qquad \Delta_s = 1 + \frac{S_s^{\rm new}}{S_0(x_t)} =: |\Delta_s| e^{i\phi_s^\Delta}$$

$$\Delta_s = r_s^2 e^{2i\theta_s} = C_{B_s} e^{2i\phi_{B_s}} = 1 + h_s e^{2i\sigma_s}$$

$$\begin{aligned}
\Delta M_s &= 2|M_{12,s}^{\rm SM}| \cdot |\Delta_s| \\
\Delta\Gamma_s &= 2|\Gamma_{12,s}| \cdot \cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right) \\
\frac{\Delta\Gamma_s}{\Delta M_s} &= \frac{|\Gamma_{12,s}|}{|M_{12,s}^{\rm SM}|} \cdot \frac{\cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)}{|\Delta_s|} \\
a_{fs}^s &= \frac{|\Gamma_{12,s}|}{|M_{12,s}^{\rm SM}|} \cdot \frac{\sin\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)}{|\Delta_s|}
\end{aligned}$$

$$\sin(\phi_s^{\rm SM}) \approx 1/240$$

For $|\Delta_s| = 0.9$ and $\phi_s^\Delta = -\pi/4$ one gets the following bounds in the **complex Δ-plane**:



ATTENTION - Φ_s vs. $-2\beta_s$

In SM both quantities small

$$\phi_s = (0.24 \pm 0.04)^\circ \qquad 2\beta_s = (2.2 \pm 0.6)^\circ (= (0.04 \pm 0.01)\text{rad})$$

TeVatron both ≈ 0, LHC will reach $2\beta_s$

- $2\beta_s := -\text{arg}[(V_{tb}V_{ts}^*)^2/(V_{cb}V_{cs}^*)^2]$, e.g. $B_s \to J/\psi + \phi$.
  $(V_{tb}V_{ts}^*)^2$ due to M_{12} and $(V_{cb}V_{cs}^*)^2$ from the ratio of $b \to c\bar{c}s$ and $\bar{b} \to \bar{c}c\bar{s}$
  Sometimes: $2\beta_s \approx -\text{arg}[(V_{tb}V_{ts}^*)^2] \approx -\text{arg}[(V_{ts}^*)^2]$ - error at per mille level.
- $\phi_s := \text{arg}[M_{12}/\Gamma_{12}]$, e.g. a_{fs}^s and $\Delta\Gamma$
  $(V_{tb}V_{ts}^*)^2$ from M_{12}
  linear combination of $(V_{cb}V_{cs}^*)^2$, $V_{cb}V_{cs}^*V_{ub}V_{us}^*$ and $(V_{ub}V_{us}^*)^2$ from Γ_{12}.
  Neglecting the latter two - which is not justified - would yield the phase $2\beta_s$.
- New physics alters the phase

$$-2\beta_s \to \phi_s^\Delta - 2\beta_s, \qquad \phi_s \to \phi_s^\Delta + \phi_s$$

ϕ_s^Δ sizeable $\Rightarrow$ standard model phases can be neglected

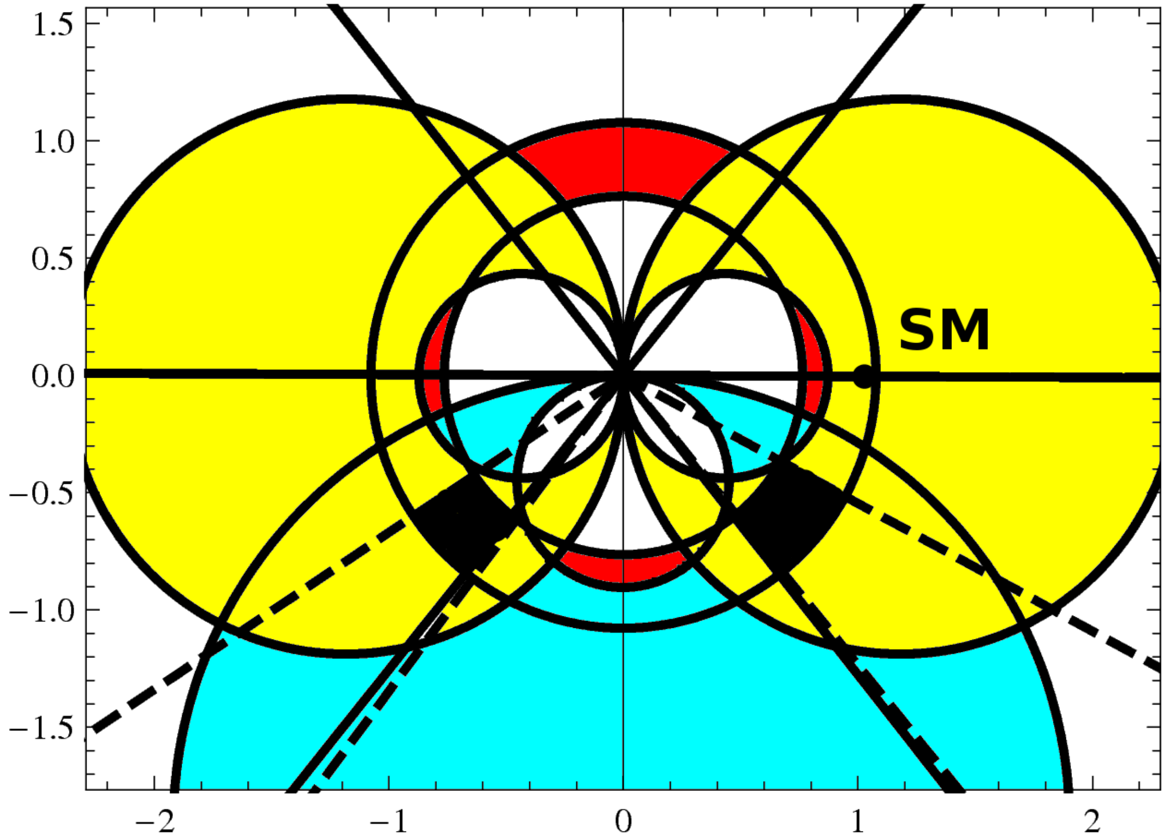
New physics in mixing III

Current exp. bounds:

- ΔM_s
- Dimuonasymmetry
- A_{sl}^s direct
- $\Delta\Gamma, \Phi_s$ $(B_s \to J/\Psi\Phi)$ combined tagged number in progress

Analyses

- A. L., U. Nierste, CKM-Fitter in preparation
- UT-Fit, arXiv:0803.0659, 3.7 σ deviation



New physics in mixing IV: Examples

- SUSY:
  e.g. Gorbahn, Jäger, Nierste, Trine;
  e.g. Kifune, Kubo, A.L.
  many, many more

- Unparticle Physics:
  A.L., arXiv:0707.1535, PRD76

  $|\Delta_s| \approx 1$ and $\phi_s^\Delta \gg \phi_s^{\rm SM}$ easily possible

- Many more ....
  - GUT
  - Extended Higgs
  - MFV
  - ...

Conclusion - Wishlist

Lessons from lifetimes

- Best: τ_{B+}/τ_{B_d} perfect agreement - but more precise values for $B_1, B_2, \epsilon_1, \epsilon_2$ needed
- Best: τ_{B_s}/τ_{B_d} Exp. 2 σ below theory - more data desireable
- Λ_b and B_c - more theoretical work necessary
- HQE seems to be in perfect shape - No signal of duality violation

Theoretical status of mixing

- Clean prediction of Γ_{12}/M_{12} in new basis
- For M_{12} and Γ_{12} precise values of decay constant needed
- For higher accuracy in Γ_{12}/M_{12} - non-perturbative parameters (B, $\tilde{B}_S$ and B_R)
- For still higher accuracy in Γ_{12}/M_{12} - α_s^2- and α_s/m_b-corrections to Γ_{12}

Experimental status of mixing

- ΔM_s and ΔM_d perfect
- First data for $\Delta\Gamma$, a_{sl} and Φ indicate a 3.7 σ? deviation from the SM
- New analysis needed - more data needed