

# The Art of Uisge Beatha Mixing



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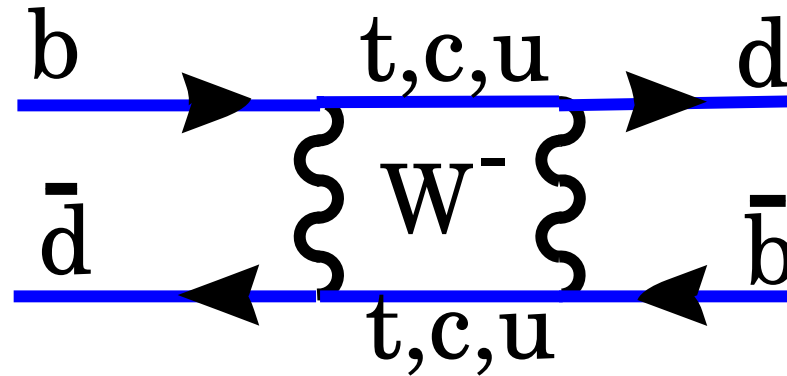
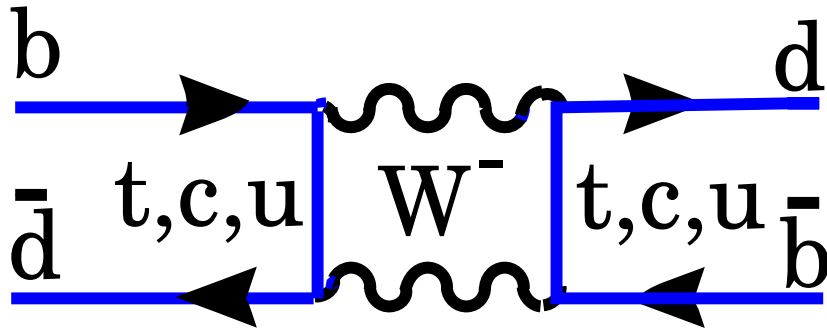
IPPP Durham



# Outline

- Mixing in the standard model
  - ◆ Introduction
  - ◆ Mass difference
  - ◆ Decay rate difference and the HQE
- Mixing beyond the standard model
  - ◆ New physics in  $M_{12}$
  - ◆ New physics in  $\Delta\Gamma_d$
  - ◆ Very new physics in mixing
- Higher precision for  $M_{12}$  and  $\Gamma_{12}$
- $B_s$  lifetimes
- Conclusion

# Introduction



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

- **Mass difference:**  $\Delta M := M_H - M_L \approx 2|M_{12}|$  (off-shell)  
 $|M_{12}|$  : heavy internal particles: t, SUSY, ...
- **Decay rate difference:**  $\Delta\Gamma := \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}| \cos \phi$  (on-shell)  
 $|\Gamma_{12}|$  : light internal particles: u, c, ... (almost) no NP!!!
- **Flavor specific/semi-leptonic CP asymmetries:** e.g.  $B_q \rightarrow X l \nu$  (semi-leptonic)

$$a_{sl} \equiv a_{fs} = \frac{\Gamma(\bar{B}_q(t) \rightarrow f) - \Gamma(B_q(t) \rightarrow \bar{f})}{\Gamma(\bar{B}_q(t) \rightarrow f) + \Gamma(B_q(t) \rightarrow \bar{f})} = \left| \frac{\Gamma_{12}}{M_{12}} \right| \sin \phi$$

# Mass difference $\Delta M$

Calculating the box diagram with an internal top-quark yields

$$M_{12,q} = \frac{G_F^2}{12\pi^2} (V_{tq}^* V_{tb})^2 M_W^2 S_0(x_t) B_{B_q} f_{B_q}^2 M_{B_q} \hat{\eta}_B$$

■ 1 loop calculation  $S_0(x_t = m_t^2/M_W^2)$

Inami, Lim, '81

■ 2-loop perturbative QCD corrections  $\hat{\eta}_B$

Buras, Jamin, Weisz, '90

■ Hadronic matrix element:  $\frac{8}{3} B_{B_q} f_{B_q}^2 M_{B_q} = \langle \bar{B}_q | (\bar{b}q)_{V-A} (\bar{b}q)_{V-A} | B_q \rangle$

$$f_{B_s} = \left\{ \begin{array}{lll} 264 \pm 19 & 2 + 1 & 1406.6192: \text{BNL '14} \\ 235 \pm 9 & 2 + 1 + 1 & 1311.2837: \text{ETM '13} \\ 233 \pm 5 & 2 + 1 & 1311.0276: \text{RBC/UKQCD '13} \\ 242 \pm 15 & SR & 1305.5432: \text{Siegen '13} \\ 224 \pm 5 & 2 + 1 + 1 & 1302.2644: \text{HPQCD '13} \\ 228 \pm 10 & 2 + 1 & 1202.4914: \text{HPQCD '12} \\ 242.0 \pm 5.1 \pm 8.0 & 2 + 1 & 1112.3051: \text{FNAL/MILC '11} \\ 225.0 \pm 2.9 \pm 2.9 & 2 + 1 & 1110.4510: \text{HPQCD '11} \end{array} \right\} = \left\{ \begin{array}{l} 250.5 \pm 32.5 \text{ ?} \\ 224 \pm 5 \text{ ?} \end{array} \right.$$

$$B_{B_s} = 1.33 \pm 0.06 \text{ HPQCD '09, } 1.32 \pm 0.05 \text{ ETM '13, } 1.22 \pm 0.13 \text{ BNL '14}$$

Important bounds on the unitarity triangle and new physics



# $\Delta M$ and $\Delta\Gamma$

## ■ Mass difference: One Operator Product Expansion (OPE)

Theory **A.L., Nierste 1102.4274** vs. Experiment : **HFAG 14**

$$\Delta M_d = 0.543 \pm 0.091 \text{ ps}^{-1}$$

$$\Delta M_d = 0.510 \pm 0.003 \text{ ps}^{-1}$$

$$\Delta M_s = 17.30 \pm 2.6 \text{ ps}^{-1}$$

$$\Delta M_s = 17.761 \pm 0.022 \text{ ps}^{-1}$$

- ◆ Perfect agreement, still room for NP
- ◆ Important bounds on the unitarity triangle and NP
- ◆ **Dominant uncertainty = Lattice**

## ■ Decay rate difference: Second OPE = Heavy Quark Expansion (HQE)

$$\Gamma_{12} = \left(\frac{\Lambda}{m_b}\right)^3 \left(\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi} \Gamma_3^{(1)} + \dots\right) + \left(\frac{\Lambda}{m_b}\right)^4 \left(\Gamma_4^{(0)} + \dots\right) + \left(\frac{\Lambda}{m_b}\right)^5 \left(\Gamma_5^{(0)} + \dots\right) + \dots$$

'96: Beneke, Buchalla; '98: Beneke, Buchalla, Greub, A.L., Nierste;

'03: Beneke, Buchalla, A.L., Nierste; '03: Ciuchini, Franco, Lubicz, Mescia, Tarantino;

'06; '11: A.L., Nierste; '07 Badin, Gabianni, Petrov



# The Heavy Quark Expansion

HQE might be questionable - relies on quark hadron duality

Energy release is small  $\Rightarrow$  naive dim. estimate: series might not converge

- Mid 90's: **Missing Charm puzzle**  $n_c^{\text{Exp.}} < n_c^{\text{SM}}$ , semi leptonic branching ratio
- Mid 90's:  **$\Lambda_b$  lifetime is too short, i.e.  $\tau(\Lambda_b) \ll \tau(B_d) = 1.519 \text{ ps}$**
- before 2003:  $\tau_{B_s}/\tau_{B_d} \approx 0.94 \neq 1$
- 2010/2011: **dimuon asymmetry too large**

## Theory arguments for HQE

- $\Rightarrow$  calculate corrections in all possible “directions”, to test convergence
- $\Rightarrow$  test reliability of HQE via lifetimes (no NP effects expected)

# The Heavy Quark Expansion

**(Almost) all discrepancies disappeared:**

- '12:  $n_c^{2011\text{PDG}} = 1.20 \pm 0.06$  vs.  $n_c^{\text{SM}} = 1.23 \pm 0.08$  **Krinner, A.L., Rauh 1305.5390**
- HFAG '03  $\tau_{\Lambda_b} = 1.229 \pm 0.080 \text{ ps}^{-1}$   $\longrightarrow$  HFAG '14  $\tau_{\Lambda_b} = 1.451 \pm 0.013 \text{ ps}^{-1}$   
**Shift by  $2.8\sigma$ !**
- **HFAG 2014:**  $\tau_{B_s}/\tau_{B_d} = 0.995 \pm 0.006$
- 2010/2011: **dimuon asymmetry too large** — **Test  $\Gamma_{12}$  with  $\Delta\Gamma_s$ !**

## Theory arguments for HQE

$\Rightarrow$  calculate corrections in all possible “directions”, to test convergence

$$\begin{aligned}\Delta\Gamma_s &= \Delta\Gamma_s^0 (1 + \delta^{\text{Lattice}} + \delta^{\text{QCD}} + \delta^{\text{HQE}}) \\ &= 0.142 \text{ ps}^{-1} (1 - 0.14 - 0.06 - 0.19)\end{aligned} \Rightarrow \text{looks ok!}$$

$\Rightarrow$  test reliability of HQE via lifetimes (no NP effects expected)

$\Rightarrow \tau(B^+)/\tau(B_d)$  experiment and theory agree within hadronic uncertainties

**Dominant uncertainties: NLO-QCD + Lattice**

# Finally $\Delta\Gamma_s$ is measured!

Finally  $\Delta\Gamma_s$  is measured! E.g. from  $B_s \rightarrow J/\psi\phi$

**LHCb Moriond 2012, 2013; ATLAS; CDF; DO; CMS**

$$\Delta\Gamma_s^{\text{Exp}} = (0.091 \pm 0.008) \text{ ps}^{-1}$$

$$\Delta\Gamma_s^{\text{SM}} = (0.087 \pm 0.021) \text{ ps}^{-1}$$

**HFAG 2014**

**A.L., Nierste 1102.4274**

Cancellation of non-perturbative uncertainties in ratios

$$\left( \frac{\Delta\Gamma_s}{\Delta M_s} \right)^{\text{Exp}} / \left( \frac{\Delta\Gamma_s}{\Delta M_s} \right)^{\text{SM}} = 1.02 \pm 0.09 \pm 0.19$$

**Dominant uncertainty = NNLO-QCD + Lattice**





# Test of our theoretical Understanding

**Most important lesson?: HQE works also for  $\Gamma_{12}$ !**

- HQE works for the decay  $b \rightarrow c\bar{c}s$
- Energy release  $M_{B_s} - 2M_{D_s} \approx 1.4 \text{ GeV}$  (momentum release: 3.5 GeV)
- Violation quark hadron duality: Theoreticians were fighting for 35 years

How precise does it work? 20%? 10%?

Still more accurate data needed!

**LHCb, ATLAS, CMS?, TeVatron, Super-Belle**

1. Apply HQE also to  $b \rightarrow c\bar{c}s$  transitions
2. Apply HQE to quantities that are sensitive to NP
3. Apply HQE also to quantities in the charm system?

# New Physics in B-mixing

- Mass and decay rate differences:  $\Delta M_s = 2|M_{12}^s|$ ,  $\Delta\Gamma_s = 2|\Gamma_{12}^s| \cos \phi_s$
- Semileptonic asymmetries:  $a_{sl}^s = |\Gamma_{12}^s/M_{12}^s| \cos \phi_s$  with  $\phi_s := \arg(-M_{12}^s/\Gamma_{12}^s)$
- CP violation in interference between mixing and decay, e.g.  
 $B_s \rightarrow \psi K^+ K^-, \psi \pi^+ \pi^-, \phi\phi, \dots$

$$-2\beta_s := \arg \left[ \frac{(V_{tb}V_{ts}^*)^2}{(V_{cb}V_{cs}^*)^2} \right],$$

- New physics

$$M_{12}^s = M_{12}^{s,\text{SM}} |\Delta_s| e^{i\phi_s^\Delta}$$

$$\Gamma_{12}^s = \Gamma_{12}^{s,\text{SM}} |\tilde{\Delta}_s| e^{i\phi_s^{\tilde{\Delta}}}$$

$$-2\beta_s + \delta_s^{\text{peng,SM}} \rightarrow \phi_s^{c\bar{c}s} = -2\beta_s + \delta_s^{\text{peng,SM}} + \delta_s^{\text{peng,NP}} + \phi_s^\Delta$$

- $\Phi_s, \Delta\Gamma_s$  from effective  $B_s$  lifetimes **Dunietz PRD52(1995)3048, hep-ph/9501287**  
 Untagged  $B_s$ -decays - fit the two exponentials with one **Hartkorn, Moser 1999**

$$\frac{\Gamma[f, t] + \Gamma[\bar{f}, t]}{2} = A e^{-\Gamma_L t} + B e^{-\Gamma_H t} = \Gamma_f e^{-\Gamma_f t} \quad \text{with} \quad \Gamma_f = \frac{\frac{A}{\Gamma_L} + \frac{B}{\Gamma_H}}{\frac{A}{\Gamma_L^2} + \frac{B}{\Gamma_H^2}}$$

see also **Dunietz, Fleischer, Nierste PRD63 (2001) 114015, hep-ph/0012219**

# Search for New Physics in B-mixing

HQE works! SM predictions: **A.L., U. Nierste, 1102.4274; A.L. 1108.1218; CKMfitter 2014**

$$\begin{aligned}
 a_{fs}^s &= (1.9 \pm 0.3) \cdot 10^{-5} & \phi_s &= 0.22^\circ \pm 0.06^\circ \\
 a_{fs}^d &= -(4.1 \pm 0.6) \cdot 10^{-4} & \phi_d &= -4.3^\circ \pm 1.4^\circ \\
 A_{sl}^b &= 0.406a_{sl}^s + 0.594a_{sl}^d = (-2.3 \pm 0.4) \cdot 10^{-4} \\
 \left| \frac{\Delta\Gamma_d}{\Gamma_d} \right| &= (4.2 \pm 0.8) \cdot 10^{-3} & \beta_s &= 0.018 \pm 0.0006
 \end{aligned}$$

CP

**Experimental bounds:**

$$\phi_s^{c\bar{c}s} = \begin{cases} 0.00 \pm 0.07 & \text{(HFAG 2014)} \\ -0.070 \pm 0.068 \pm 0.008 & B_s \rightarrow \psi\pi\pi \text{ (1405.4140)} \\ 0.17 \pm 0.15 \pm 0.03 & B_s \rightarrow \phi\phi \text{ (1407.2222)} \end{cases}$$

$$\left| \frac{\Delta\Gamma_d}{\Gamma_d} \right| = (1 \pm 10) \cdot 10^{-3} \quad \text{(HFAG 14)}$$

$$A_{sl}^b = -(7.87 \pm 1.72 \pm 0.93) \cdot 10^{-3} \quad \text{(D0, 1106.6308)}$$



# Search for New Physics in B-Mixing

Simplified model independent analysis: **A.L., Nierste, '06**

$$\Gamma_{12,s} = \Gamma_{12,s}^{\text{SM}}, \quad M_{12,s} = M_{12,s}^{\text{SM}} \cdot \Delta_s; \quad \Delta_s = |\Delta_s| e^{i\phi_s^\Delta}$$

i.e. no penguins and no NP in  $\Gamma_{12}$ !

$$\Delta M_s = 2|M_{12,s}^{\text{SM}}| \cdot |\Delta_s|$$

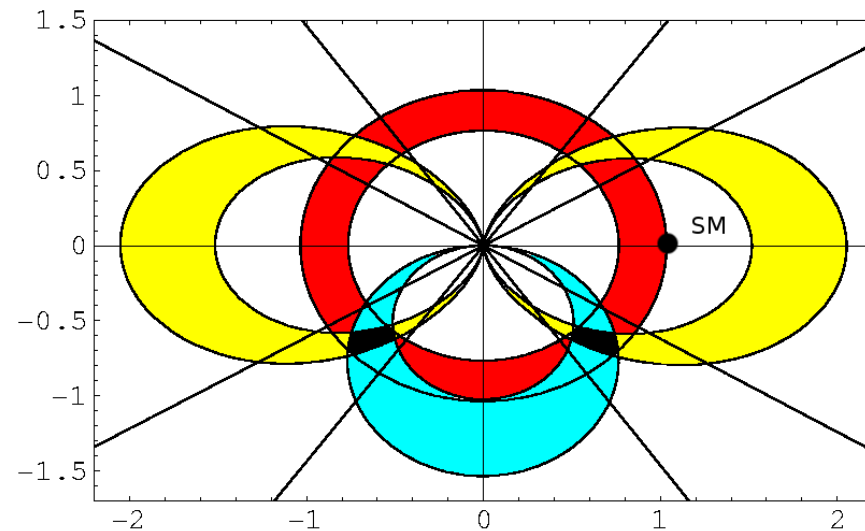
$$\Delta\Gamma_s = 2|\Gamma_{12,s}| \cdot \cos(\phi_s^{\text{SM}} + \phi_s^\Delta)$$

$$\frac{\Delta\Gamma_s}{\Delta M_s} = \frac{|\Gamma_{12,s}|}{|M_{12,s}^{\text{SM}}|} \cdot \frac{\cos(\phi_s^{\text{SM}} + \phi_s^\Delta)}{|\Delta_s|}$$

$$a_{fs}^s = \frac{|\Gamma_{12,s}|}{|M_{12,s}^{\text{SM}}|} \cdot \frac{\sin(\phi_s^{\text{SM}} + \phi_s^\Delta)}{|\Delta_s|}$$

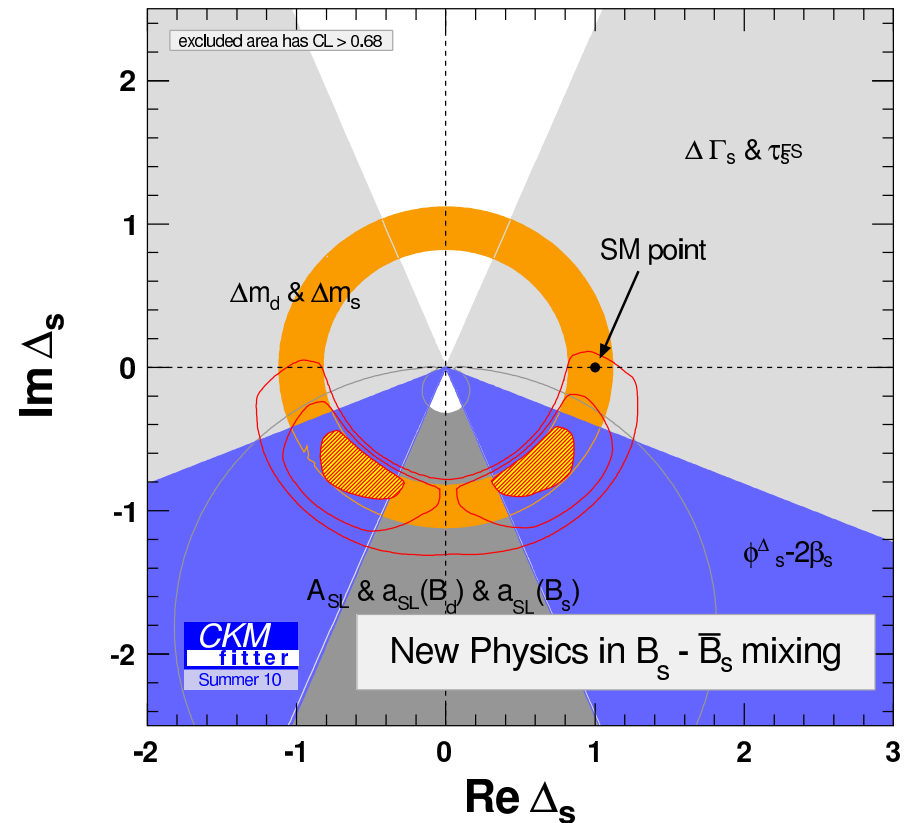
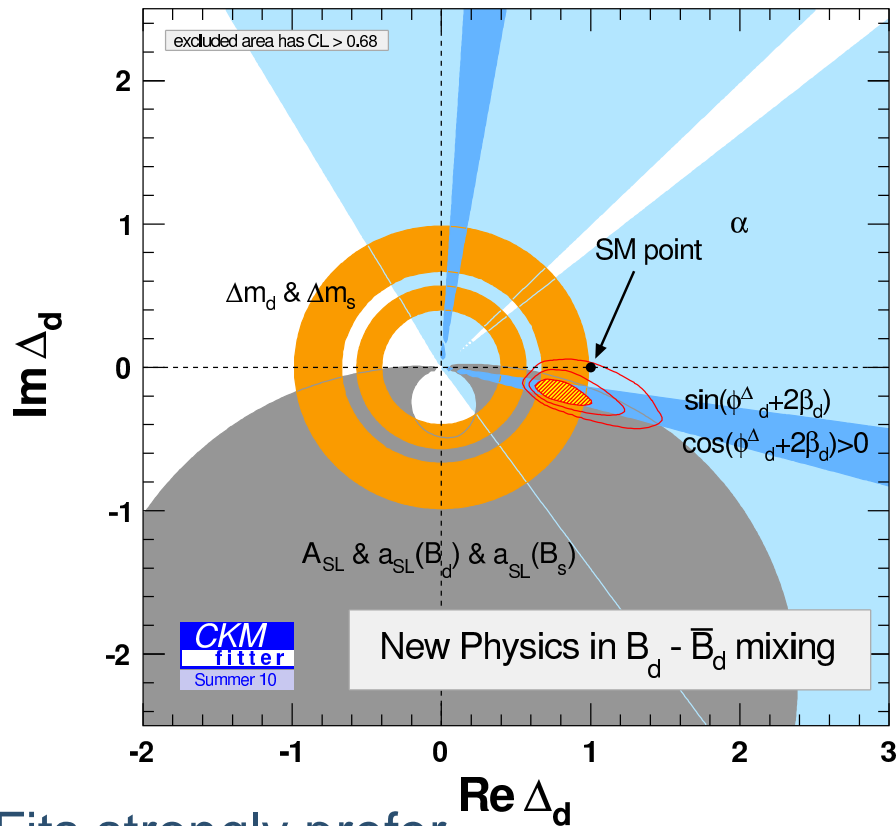
$$\sin(\phi_s^{\text{SM}}) \approx 1/240$$

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



# Search for New Physics in B-Mixing

Combine all data before summer 2010 and **neglect penguins**  
fit of  $\Delta_d$  and  $\Delta_s$  **A.L.. Nierste. CKMfitter 1008.1593**

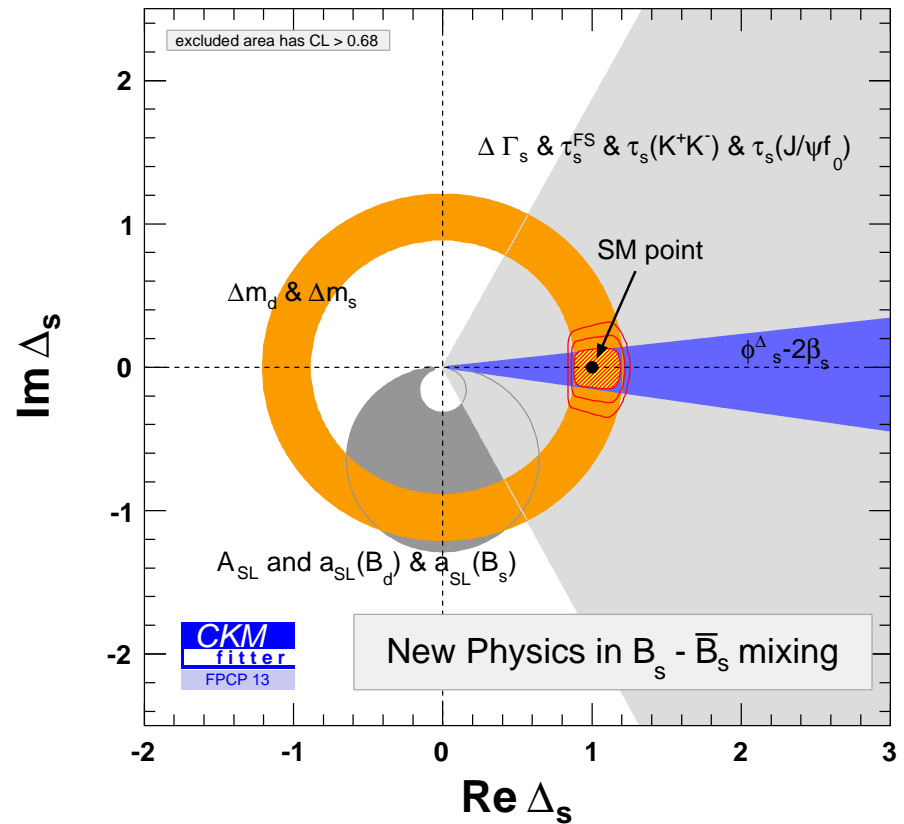
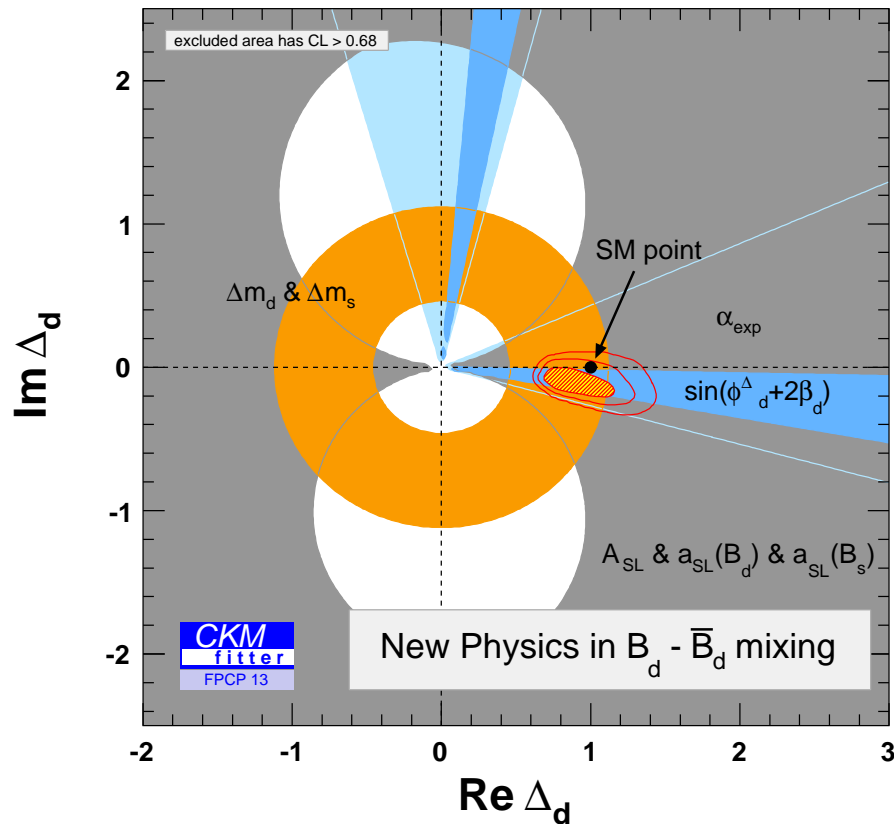


Fits strongly prefer

- large new physics effects in the  $B_s$ -system
- some new physics effects in the  $B_d$ -system

# Search for New Physics in B-Mixing

Combine all data till FPCP 2013 and neglect penguins  
fit of  $\Delta_d$  and  $\Delta_s$ ; update of A.L., Nierste, CKMfitter 1203.0238v2



- SM seems to be perfect
- Still quite some room for NP

# Search for NP in B-Mixing: $A_{sl}^b$ ?

$$A_{sl}^b \approx \frac{1}{2} \frac{|\Gamma_{12,d}|}{|M_{12,d}^{\text{SM}}|} \cdot \frac{\sin(\phi_d^{\text{SM}} + \phi_d^{\Delta})}{|\Delta_d|} + \frac{1}{2} \frac{|\Gamma_{12,s}|}{|M_{12,s}^{\text{SM}}|} \cdot \frac{\sin(\phi_s^{\text{SM}} + \phi_s^{\Delta})}{|\Delta_s|}$$

**BUT:** The experimental number is larger than “possible”! **A.L. 1205.1444, 1106.3200**

1. Huge (= several 100 %) duality violations in  $\Gamma_{12}^s$ ?  $\rightarrow$  NO! see  $\Delta\Gamma_s$
2. Huge NP in  $\Gamma_{12}^s$ ?  $\rightarrow$  NO! this also affects observables like  $\tau_{B_s}/\tau_{B_d}, n_c, \dots$   
**But still some sizable NP possible** - investigate e.g.  $n_c$  **Bobeth, Haisch 1109.1826**
3. Look at experimental side
  - Statistical fluctuation - **D0 update 1310.0447**
  - Cross-check via individual asymmetries - **LHCb, D0, BaBar**  
 $\Rightarrow$  consistent with SM, but not yet in conflict with  $A_{sl}^b$
  - Some systematics neglected - **Borissov, Hoeneisen 1303.0175**  
**Discrepancy still more than  $3\sigma$**  - also dependence on  $\Delta\Gamma_d$   
 $\Rightarrow A_{sl}^b$  points towards effects in  $a_{sl}^d, a_{sl}^s$  and  $\Delta\Gamma_d$  - look also somewhere else



# Search for NP in B-Mixing: $A_{sl}^b$ ?

- New measurements for the individual semi leptonic CP asymmetries

$$a_{sl}^s = -0.06 \pm 0.50 \pm 0.36\% \quad \text{LHCb 1308.1048}$$

$$a_{sl}^s = -1.12 \pm 0.74 \pm 0.17\% \quad \text{D0 1207.1769}$$

$$a_{sl}^d = 0.68 \pm 0.45 \pm 0.14\% \quad \text{D0 1208.5813}$$

$$a_{sl}^d = 0.06 \pm 0.17^{+0.38}_{-0.32}\% \quad \text{BaBar 1305.1575}$$

All numbers are consistent with the SM  
(no confirmation of large new physics effects)  
but also consistent with the value of the dimuon asymmetry

**more data urgently needed**

- New interpretation of the dimuon asymmetry **Borissov, Hoeneisen 1303.0175**

$$A_{sl}^b = C_d a_{sl}^d + C_s a_{sl}^s + C_\Gamma \frac{\Delta\Gamma_d}{\Gamma_d}$$

**There is still sizable space for NP in  $\Delta\Gamma_d$**





# New physics in $\Delta\Gamma_d$ ?

- $\Delta\Gamma_s$  cannot be enhanced dramatically by new physics - Bobeth, Haisch 2011
- $\Delta\Gamma_d$  could in principle be enhanced dramatically - Bobeth, Haisch, A.L., Pecjak, Tetlalmatzi-Xolocotzi 2014

## Comparison

- $\Delta\Gamma_s$  dominated by  $b \rightarrow c\bar{c}s$ :  $B(b \rightarrow c\bar{c}s) = (23.7 \pm 1.3)\%$  Krinner, A.L., Rauh 2013
- $\Delta\Gamma_d$  dominated by  $b \rightarrow c\bar{c}d$ :  $B(b \rightarrow c\bar{c}d) = (1.31 \pm 0.07)\%$  Krinner, A.L., Rauh 2013
- $\Delta\Gamma_s$  is completely dominated by  $b \rightarrow c\bar{c}s$ ,  $\Delta\Gamma_d$  has also sizable contributions from  $b \rightarrow c\bar{u}d$  and  $b \rightarrow u\bar{u}d$ , which **cancel** to some extent

## Enhancement via

- Violations of CKM duality
- New **(almost unconstrained)**  $bd\tau\tau$  operators
- New physics in current-current operators  $Q_1$  and  $Q_2$

# Search for enhanced $b \rightarrow d, s\tau\tau$ transitions I

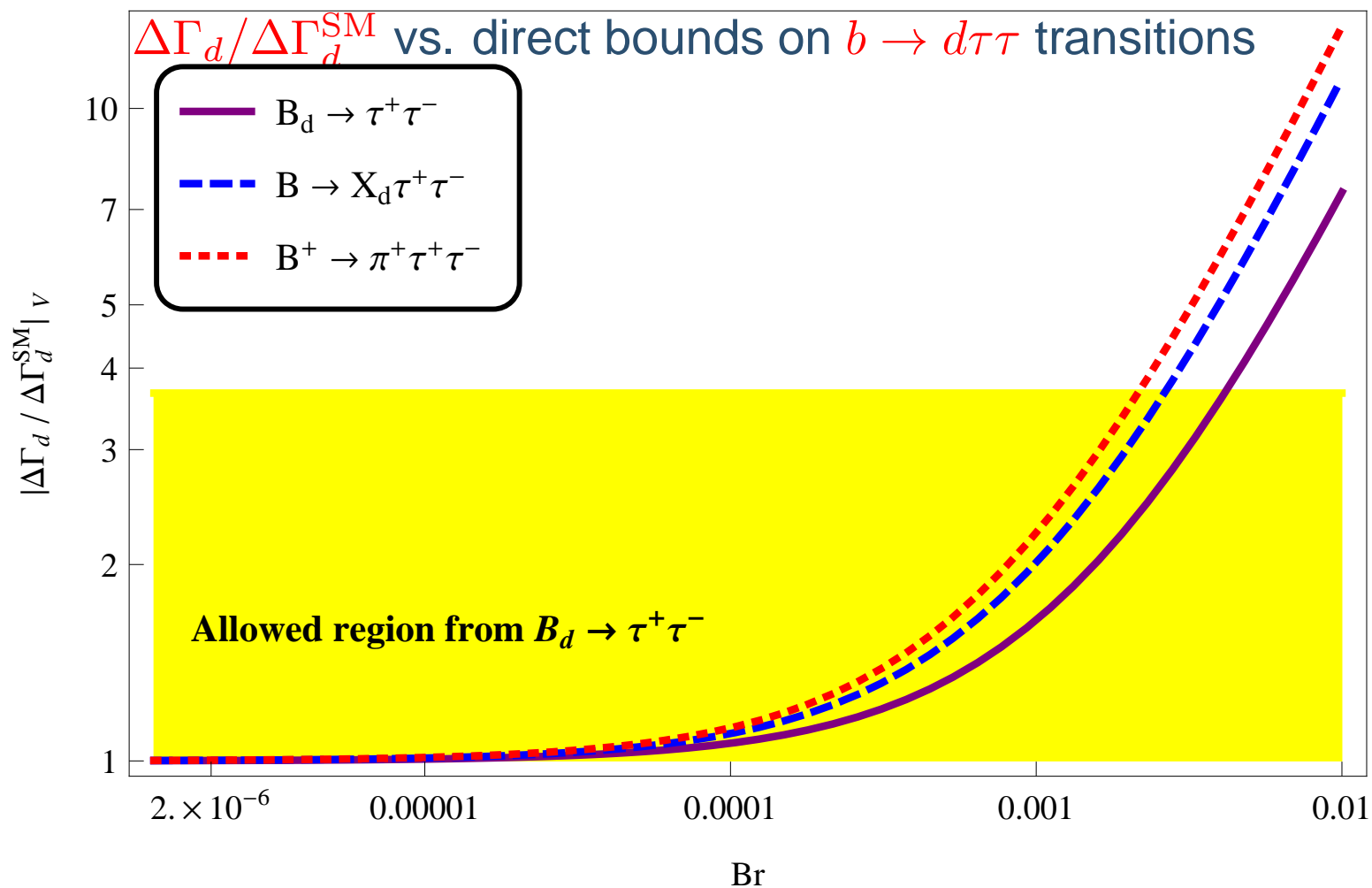
A class of (almost) invisible decays

- $b \rightarrow s\tau\tau$  can enhance  $\Delta\Gamma_s$  and  $a_{sl}^s$ . It is constrained by
  - ◆  $B_s \rightarrow \tau\tau < 2.7\%$  **indirect** from  $\tau(B_s)/\tau(B_d)$
  - ◆  $B \rightarrow X_s\tau\tau < 2.7\%$  **indirect** from  $\tau(B_s)/\tau(B_d)$
  - ◆  $B^+ \rightarrow K^+\tau\tau < 3.3 \cdot 10^{-3}$  **direct** from **BaBar 2010** $\Rightarrow$  Enhancement of up to **35%** in  $\Delta\Gamma_s$  possible ( $\approx$  hadronic uncertainties)  
 $\Rightarrow$  **Improve bounds on  $b \rightarrow s\tau\tau$ !** **Bobeth, Haisch 2011**

$\Gamma_{12}^s$  is dominated by the CKM favoured decay  $b \rightarrow c\bar{c}s$ , a huge effect would be seen everywhere -  $\Gamma_{12}^d$  looks more promising

- $b \rightarrow d\tau\tau$  can enhance  $\Delta\Gamma_d$  and  $a_{sl}^d$ . It is constrained by
  - ◆  $B_d \rightarrow \tau\tau < 4.1 \cdot 10^{-3}$  **direct** from **BaBar 2006**
  - ◆  $B \rightarrow X_d\tau\tau < 2.7\%$  **indirect** from  $\tau(B_s)/\tau(B_d)$
  - ◆  $B^+ \rightarrow \pi^+\tau\tau < 2.7\%$  **indirect** from  $\tau(B_s)/\tau(B_d)$ $\Rightarrow$  Enhancement of up to **270%** in  $\Delta\Gamma_d$  possible  
**This might solve the dimuon asymmetry!  $\Rightarrow$  Improve bounds on  $b \rightarrow d\tau\tau$ !**  
**Bobeth, Haisch, AL, Pecjak, Tetlalmatzi-Xolocotzi, 2014**

# Search for enhanced $b \rightarrow d, s\tau\tau$ transitions II

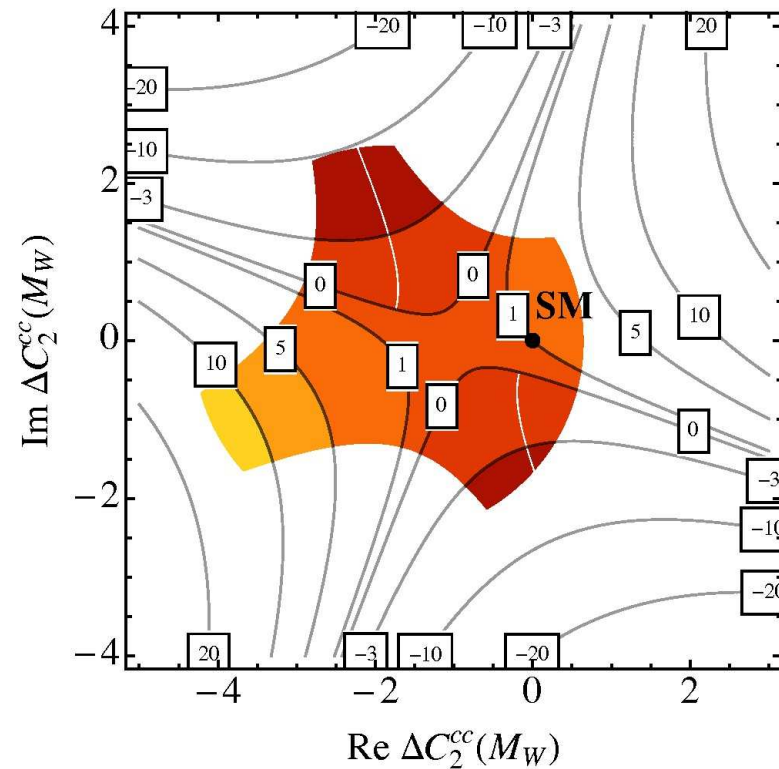
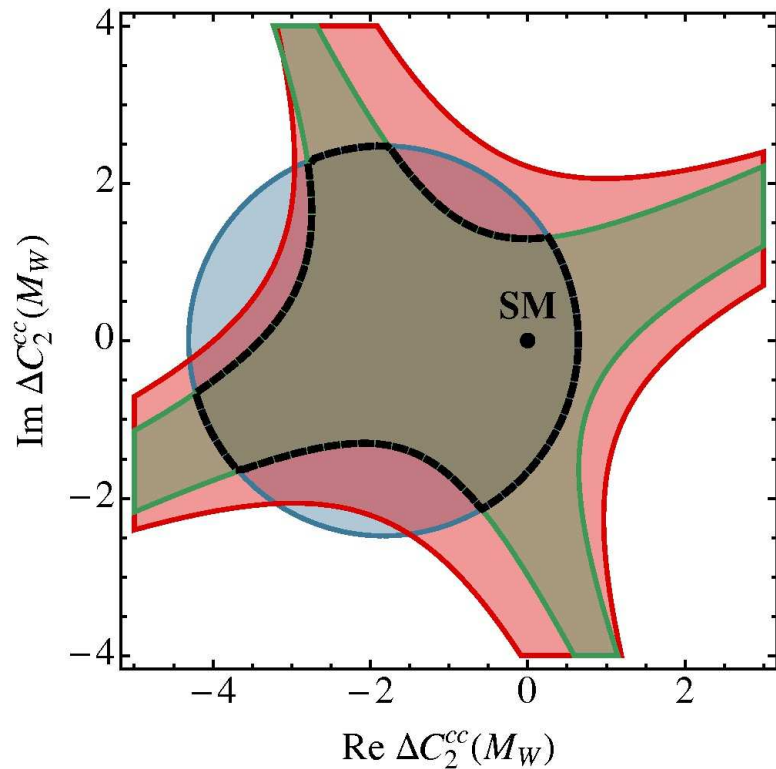


Bobeth, Haisch, AL, Pecjak, Tetlalmatzi-Xolocotz, 2014

# New physics in $\Delta\Gamma_d$

New physics contributions to the current-current operators  $Q_1$  and  $Q_2$

The decays  $b \rightarrow c\bar{c}d, c\bar{u}d, u\bar{c}d, u\bar{u}d$  can get different new physics contributions to the Wilson coefficients (the SM-one is universal)



Constraints from  $B \rightarrow \pi\pi, \rho\pi, \rho\rho, D^*\pi, B \rightarrow X_d\gamma, \sin 2\beta$  still allow enhancements of  $\Delta\Gamma_d$  by more than a factor of five

# Search for very new physics

Test of the fundamentals of Quantum Mechanics with B-mixing

**Bertlmann, Grimus 1997**

Test decoherence in Quantum Mechanics

$$O = |A_1 + A_2|^2 = |A_1|^2 + |A_2|^2 + 2\text{Re}(A_1 A_2^*) \rightarrow |A_1|^2 + |A_2|^2 + 2(1 - \zeta)\text{Re}(A_1 A_2^*)$$

In Quantum Mechanics  $\zeta = 0$  holds, test experimentally via

$$R = \frac{N^{++} + N^{--}}{N^{+-} + N^{-+}} = \frac{\text{like-sign dilepton events}}{\text{opposite-sign dilepton events}}$$

$$= \frac{1}{2} \left( \left| \frac{p}{q} \right|^2 + \left| \frac{q}{p} \right|^2 \right) \frac{x^2 + y^2 + \zeta \left[ y^2 \frac{1+x^2}{1-y^2} + x^2 \frac{1-y^2}{1+x^2} \right]}{2 + x^2 - y^2 + \zeta \left[ y^2 \frac{1+x^2}{1-y^2} - x^2 \frac{1-y^2}{1+x^2} \right]}$$

New analysis:  $x$  and  $y$  from **HFAG 2014** and  $R$  from **ARGUS 1994, CLEO 1993**

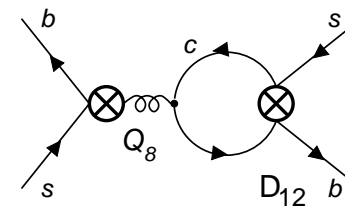
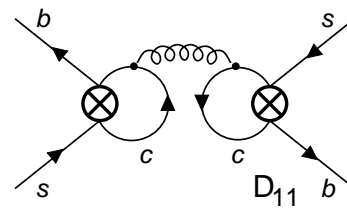
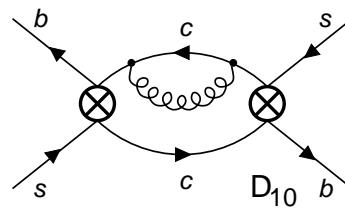
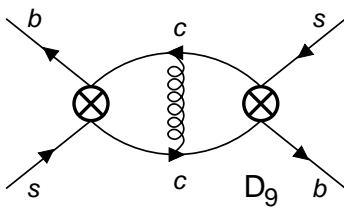
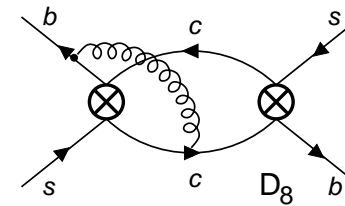
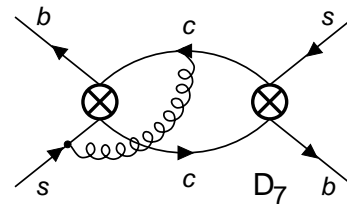
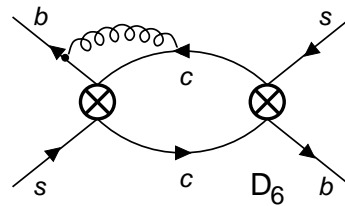
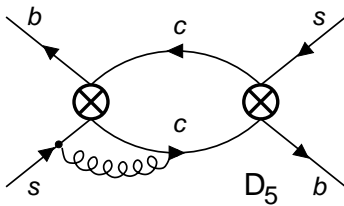
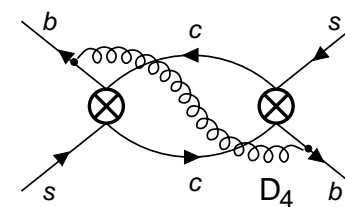
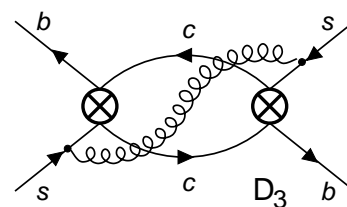
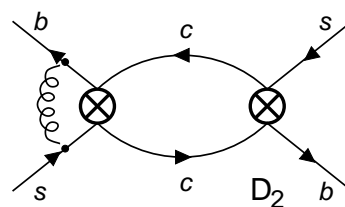
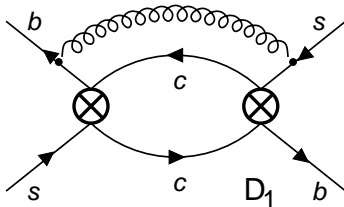
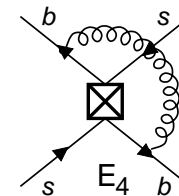
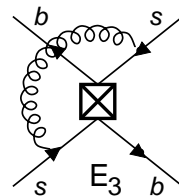
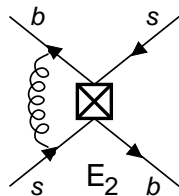
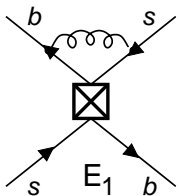
$$\zeta = -0.26^{+0.30}_{-0.28}$$

$\delta R$	$\pm 10\%$	$\pm 5\%$	$\pm 2\%$
$\delta \zeta$	$+45.2\%$ $-43.8\%$	$+22.8\%$ $-22.4\%$	$+10.0\%$ $-9.98\%$

**Hodges, Hulme, Kvedaraite, A.L., Richings, Shen, Waite, to appear**

# Theory Prediction for $\Delta\Gamma_s$

Calculating the following diagrams





# Theory Prediction for $\Delta\Gamma_s$

one gets Wilson coefficients of the following operators

$$Q = (\bar{b}_i s_i)_{V-A} \cdot (\bar{b}_j s_j)_{V-A}$$

$$\tilde{Q}_S = (\bar{b}_i s_j)_{S-P} \cdot (\bar{b}_i s_j)_{S-P}$$

$$\langle \bar{B}_s | Q | B_s \rangle = \frac{8}{3} f_{B_s}^2 M_{B_s}^2 B$$

$$\langle \bar{B}_s | \tilde{Q}_S | B_s \rangle = \frac{1}{3} f_{B_s}^2 M_{B_s}^2 \tilde{B}'_S = \frac{1}{3} f_{B_s}^2 M_{B_s}^2 \frac{M_{B_s}^2}{(\bar{m}_b + \bar{m}_s)^2} \tilde{B}_S$$

$f_{B_s}$ ,  $B$  and  $\tilde{B}_S$  have to be determined non-perturbatively!



# Theory Prediction for $\Delta\Gamma_s$

Expanding also in the small  $s$  momenta one get contributions of dimension 7

$$R_0 = Q_s + \tilde{Q}_S + \frac{1}{2}Q$$

$$R_1 = \frac{m_s}{m_b} (\bar{b}_i s_i)_{S-P} (\bar{b}_j s_j)_{S+P}$$

$$R_2 = \frac{1}{m_b^2} (\bar{b}_i \overleftarrow{D}_\rho \gamma^\mu (1 - \gamma_5) D^\rho s_i) (\bar{b}_j \gamma_\mu (1 - \gamma_5) s_j)$$

$$R_3 = \frac{1}{m_b^2} (\bar{b}_i \overleftarrow{D}_\rho (1 - \gamma_5) D^\rho s_i) (\bar{b}_j (1 - \gamma_5) s_j)$$

$$\tilde{R}_i = \tilde{R}_i(R_j)$$

There exist no non-perturbative determinations of these operators

A first estimate with QCD sum rules was made by **Mannel, Pecjak, Pivovarov**

Current estimates rely on vacuum insertion approximation



# Theory Prediction for $\Delta\Gamma_s$

$\Delta\Gamma_s^{\text{SM}}$	2011	2006
Central Value	$0.087 \text{ ps}^{-1}$	$0.096 \text{ ps}^{-1}$
$\delta(\mathcal{B}_{\tilde{R}_2})$	17.2%	15.7%
$\delta(f_{B_s})$	13.2%	33.4%
$\delta(\mu)$	7.8%	13.7%
$\delta(\tilde{\mathcal{B}}_{S,B_s})$	4.8%	3.1%
$\delta(\mathcal{B}_{R_0})$	3.4%	3.0%
$\delta(V_{cb})$	3.4%	4.9%
$\delta(\mathcal{B}_{B_s})$	2.7%	6.6%
...	....	...
$\sum \delta$	24.5%	40.5%

- Additional Bag parameters at dimension 6 and 7 for  $\Gamma_{12}$
- $\alpha_s/m_b$  corrections for  $\Gamma_{12}$
- $\alpha_s^2$  corrections for  $\Gamma_{12}$  first step: Asatrian, Hovhannisyan, Yeghiazaryan, arXiv:1210.7939

# Effective $B_s$ lifetimes

$$\tau_{B_q \rightarrow f} = \frac{1}{\Gamma_q} \frac{1}{1 - y_q^2} \left( \frac{1 + 2\mathcal{A}_{\Delta\Gamma_q}^f y_q + y_q^2}{1 + \mathcal{A}_{\Delta\Gamma_q}^f y_q} \right)$$

with

$$\mathcal{A}_{\Delta\Gamma_q}^f = -\frac{2\text{Re}(\lambda_f)}{1 + |\lambda_f|^2}, \quad \lambda_f = \frac{q}{p} \frac{\bar{A}_f}{A_f}, \quad y_q = \frac{\Delta\Gamma_q}{2\Gamma_q}$$

- Flavour-specific  $\mathcal{A}_{\Delta\Gamma_q}^f = 0$

$$\tau(B_s \rightarrow \pi^+ K^-) = 1.60(6)(1) \text{ ps} \quad \text{LHCb1406.7204}$$

$$\tau(B_s \rightarrow D_s^+ D^-) = 1.52(15)(1) \text{ ps} \quad \text{LHCb1312.1217}$$

- $\mathcal{A}_{\Delta\Gamma_q}^f$  from **Fleischer, Knegjens 2010,11**

$$\tau(B_s \rightarrow K^+ K^-) = 1.407(16)(7) \text{ ps} \quad \text{LHCb1406.7204}$$

- CP-even  $\tau_L$

$$\tau(B_s \rightarrow D_s^+ D_s^-) = 1.406(18) \text{ ps} \quad \text{LHCb1406.7204}$$

- CP-odd  $\tau_H$

$$\tau(B_s \rightarrow \psi f_0) = 1.656(33) \text{ ps} \quad \text{HFAG2014}$$

# What did we learn?

## ■ Test of our theoretical Understanding

- ◆ SM and CKM work **perfectly**
- ◆ HQE work also **perfectly**

	HQE	HFAG 2014	Ref.
$\frac{\Delta\Gamma_s}{\Delta M_s}$	$0.0050 \cdot (1 \pm 0.19)$	$0.0051 \cdot (1 \pm 0.09)$	A.L., Nierste1102.4274
$\frac{\tau(\Lambda_b)}{\tau(B_d)}$	$0.935 \pm 0.054$	$0.955 \pm 0.009$	A.L., 1405.3601

**No space for sizable duality violations**

## ■ Search for NP

- ◆ No huge effects seen, but **still some sizable space left**

Test:  $\Delta\Gamma_d, B \rightarrow X\tau\tau, \tau(B_s)/\tau(B_d), a_{sl}, R, C_{1,2}\dots$

## ■ Life becomes harder: higher precision in experiment and theory needed

- ◆ **Non-perturbative parameters - lattice - corrent limitation of progress in HQE**
- ◆ **Higher order perturbative corrections**
- ◆ **Experimentally more difficult observables**
- ◆ **Alternative non-perturbative methods (LCSR,...)**
- ◆ **Take penguins into account**