The Art of
Uisge Beatha Mixing

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Outline

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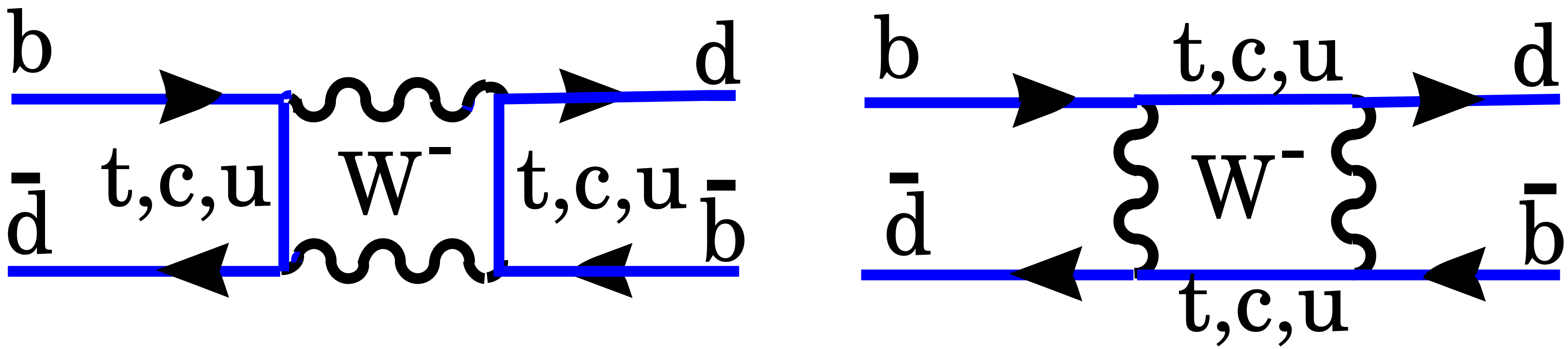
  - New physics in $\Delta\Gamma_d$
  - Very new physics in mixing
- Higher precision for M_{12} and Γ_{12}
- B_s lifetimes
- Conclusion

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. $B_q \to X l \nu$ (*semi-leptonic*)

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

Mass difference ΔM

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

$f_{B_s} =$

264 ± 19	$2+1$	**1406.6192: BNL '14**
235 ± 9	$2+1+1$	**1311.2837: ETM '13**
233 ± 5	$2+1$	**1311.0276: RBC/UKQCD '13**
242 ± 15	SR	**1305.5432: Siegen '13**
224 ± 5	$2+1+1$	**1302.2644: HPQCD '13**
228 ± 10	$2+1$	**1202.4914: HPQCD '12**
$242.0 \pm 5.1 \pm 8.0$	$2+1$	**1112.3051: FNAL/MILC '11**
$225.0 \pm 2.9 \pm 2.9$	$2+1$	**1110.4510: HPQCD '11**

$= \begin{cases} 250.5 \pm 32.5 \ ? \\ 224 \pm 5 \ ? \end{cases}$

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

Important bounds on the unitarity triangle and new physics

ΔM and $\Delta\Gamma$

- **Mass difference:** One Operator Product Expansion (OPE)

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

$$\Delta M_d = 0.543 \pm 0.091 \text{ ps}^{-1} \qquad \Delta M_d = 0.510 \pm 0.003 \text{ ps}^{-1}$$
$$\Delta M_s = 17.30 \pm 2.6 \text{ ps}^{-1} \qquad \Delta M_s = 17.761 \pm 0.022 \text{ ps}^{-1}$$

  - 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)

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

'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 $n_c^{\rm Exp.} < n_c^{\rm SM}$, semi leptonic branching ratio
- Mid 90's: Λ_b lifetime is too short, i.e. $\tau(\Lambda_b) \ll \tau(B_d) = 1.519$ 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 $\tau_{\Lambda_b} = 1.229 \pm 0.080$ ps^{-1} $\longrightarrow$ HFAG '14 $\tau_{\Lambda_b} = 1.451 \pm 0.013$ ps^{-1}

  Shift by 2.8σ!

- **HFAG 2014:** $\tau_{B_s}/\tau_{B_d} = 0.995 \pm 0.006$
- 2010/2011: dimuon asymmetry too large — Test Γ_{12} with $\Delta\Gamma_s$!

Theory arguments for HQE

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

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

$\Rightarrow$ 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 $B_s \to J/\psi\phi$

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

$$\Delta\Gamma_s^{\rm Exp} = (0.091 \pm 0.008)\,\text{ps}^{-1}$$
$$\Delta\Gamma_s^{\rm SM} = (0.087 \pm 0.021)\,\text{ps}^{-1}$$

HFAG 2014

A.L.,Nierste 1102.4274

Cancellation of non-perturbative uncertainties in ratios

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

Dominant uncertainty = NNLO-QCD + Lattice

Test of our theoretical Understanding

Most important lesson?: HQE works also for Γ_{12}!

- HQE works for the decay $b \to c\bar{c}s$
- Energy release $M_{B_s} - 2M_{D_s} \approx 1.4$ 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 $b \to c\bar{c}s$ 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: $a_{sl}^s = |\Gamma_{12}^s / M_{12}^s| \sin\phi_s$ with $\phi_s := \arg(-M_{12}^s/\Gamma_{12}^s)$
- CP violation in interference between mixing and decay, e.g
$B_s \to \psi K^+ K^-, \psi\pi^+\pi^-, \phi\phi$,...

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

- New physics

$$\begin{aligned} M_{12}^s &= M_{12}^{s,\mathrm{SM}} |\Delta_s| e^{i\phi_s^\Delta} \\ \Gamma_{12}^s &= \Gamma_{12}^{s,\mathrm{SM}} |\tilde{\Delta}_s| e^{i\phi_s^{\tilde{\Delta}}} \\ -2\beta_s + \delta_s^{\mathrm{peng,SM}} &\to \phi_s^{c\bar{c}s} = -2\beta_s + \delta_s^{\mathrm{peng,SM}} + \delta_s^{\mathrm{peng,NP}} + \phi_s^\Delta \end{aligned}$$

- $\Phi_s, \Delta\Gamma_s$ 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**

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

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**

$$a_{fs}^s = (1.9 \pm 0.3) \cdot 10^{-5} \qquad \phi_s = 0.22^\circ \pm 0.06^\circ$$

$$a_{fs}^d = -(4.1 \pm 0.6) \cdot 10^{-4} \qquad \phi_d = -4.3^\circ \pm 1.4^\circ$$

$$A_{sl}^b = 0.406 a_{sl}^s + 0.594 a_{sl}^d = (-2.3 \pm 0.4) \cdot 10^{-4}$$

$$\left| \frac{\Delta \Gamma_d}{\Gamma_d} \right| = (4.2 \pm 0.8) \cdot 10^{-3} \qquad \beta_s = 0.018 \pm 0.0006$$

Experimental bounds:

$$\phi_s^{c\bar{c}s} = 0.00 \pm 0.07$$ **(HFAG 2014)**

$$\phi_s^{c\bar{c}s} = -0.070 \pm 0.068 \pm 0.008 \quad B_s \to \psi\pi\pi$$ **(1405.4140)**

$$\phi_s^{s\bar{s}s} = 0.17 \pm 0.15 \pm 0.03 \quad B_s \to \phi\phi$$ **(1407.2222)**

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

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

Search for New Physics in B-Mixing

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

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

i.e. no penguins and no NP in Γ_{12}!

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

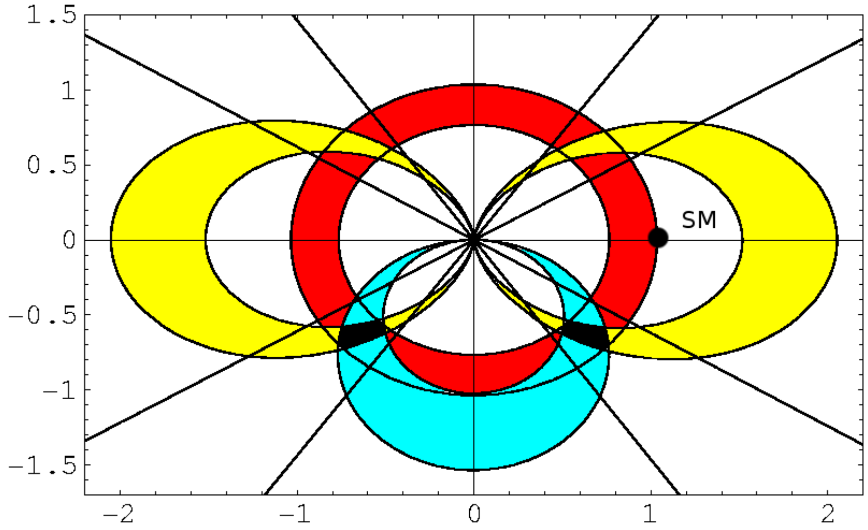
$$\Delta \Gamma_s = 2|\Gamma_{12,s}| \cdot \cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)$$

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

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

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

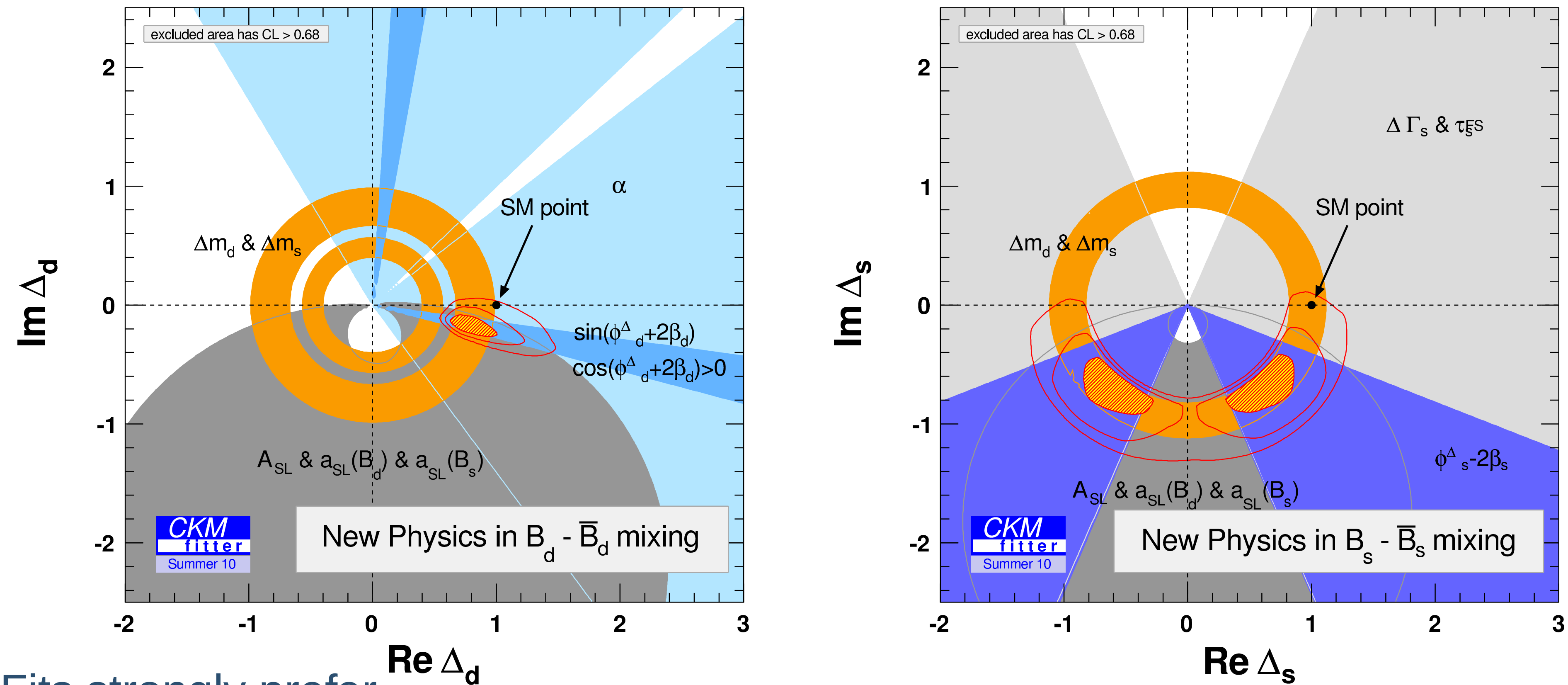
For $|\Delta_s| = 0.9$ and $\phi_s^\Delta = -\pi/4$ one gets the following bounds in the **complex Δ-plane**:



Search for New Physics in B-Mixing

Combine all data before summer 2010 and **neglect penguins**

fit of Δ_d and Δ_s **A.L.. Nierste. CKMfitter 1008.1593**



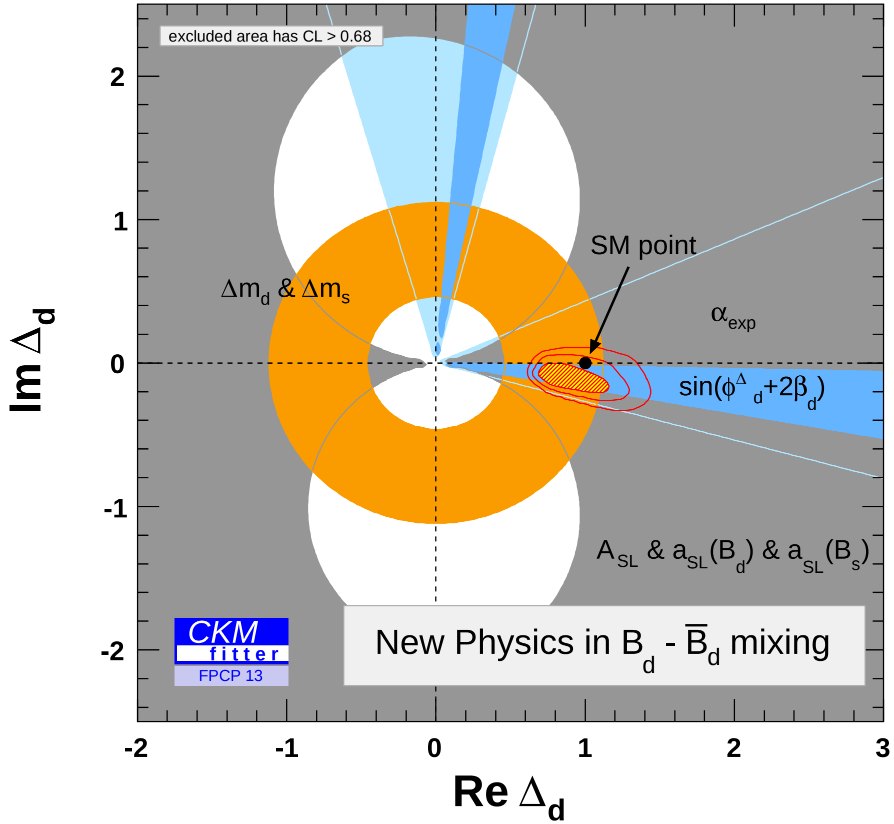
Fits strongly prefer

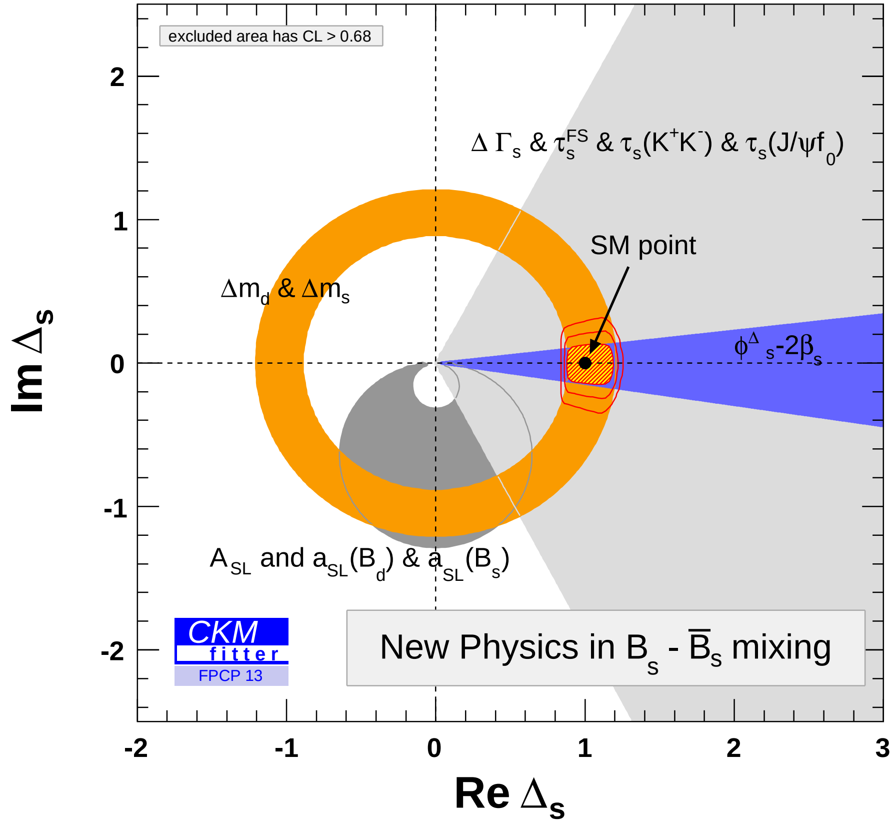
- **large new physics effects in the B_s-system**
- **some new physics effects in the B_d-system**

Search for New Physics in B-Mixing

Combine all data till FPCP 2013 and neglect penguins

fit of Δ_d and Δ_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?

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

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

1. Huge (= several 100 $\%$) duality violations in Γ_{12}^s? $\rightarrow$ NO! see $\Delta\Gamma_s$
2. Huge NP in Γ_{12}^s? $\rightarrow$ NO! this also affects observables like $\tau_{B_s}/\tau_{B_d}, n_c, ...$
   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 3σ - **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^b_{sl}?

- New measurements for the individual semi leptonic CP asymmetries

$$a^s_{sl} = -0.06 \pm 0.50 \pm 0.36\% \quad \text{LHCb 1308.1048}$$
$$a^s_{sl} = -1.12 \pm 0.74 \pm 0.17\% \quad \text{D0 1207.1769}$$
$$a^d_{sl} = 0.68 \pm 0.45 \pm 0.14\% \quad \text{D0 1208.5813}$$
$$a^d_{sl} = 0.06 \pm 0.17^{+0.38}_{-0.32}\% \quad \text{BaBar 1305.1575}$$

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**

$$A^b_{sl} = C_d a^d_{sl} + C_s a^s_{sl} + C_\Gamma \frac{\Delta\Gamma_d}{\Gamma_d}$$

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

A class of (almost) invisible decays

- $b \to s\tau\tau$ can enhance $\Delta\Gamma_s$ and a_{sl}^s. It is constrained by
  - $B_s \to \tau\tau < 2.7\%$ **indirect** from $\tau(B_s)/\tau(B_d)$
  - $B \to X_s\tau\tau < 2.7\%$ **indirect** from $\tau(B_s)/\tau(B_d)$
  - $B^+ \to K^+\tau\tau < 3.3 \cdot 10^{-3}$ **direct** from **BaBar 2010**

  $\Rightarrow$ Enhancement of up to **35**$\%$ in $\Delta\Gamma_s$ possible ($\approx$ hadronic uncertainties)

  $\Rightarrow$ **Improve bounds on** $b \to s\tau\tau$**!** **Bobeth, Haisch 2011**

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

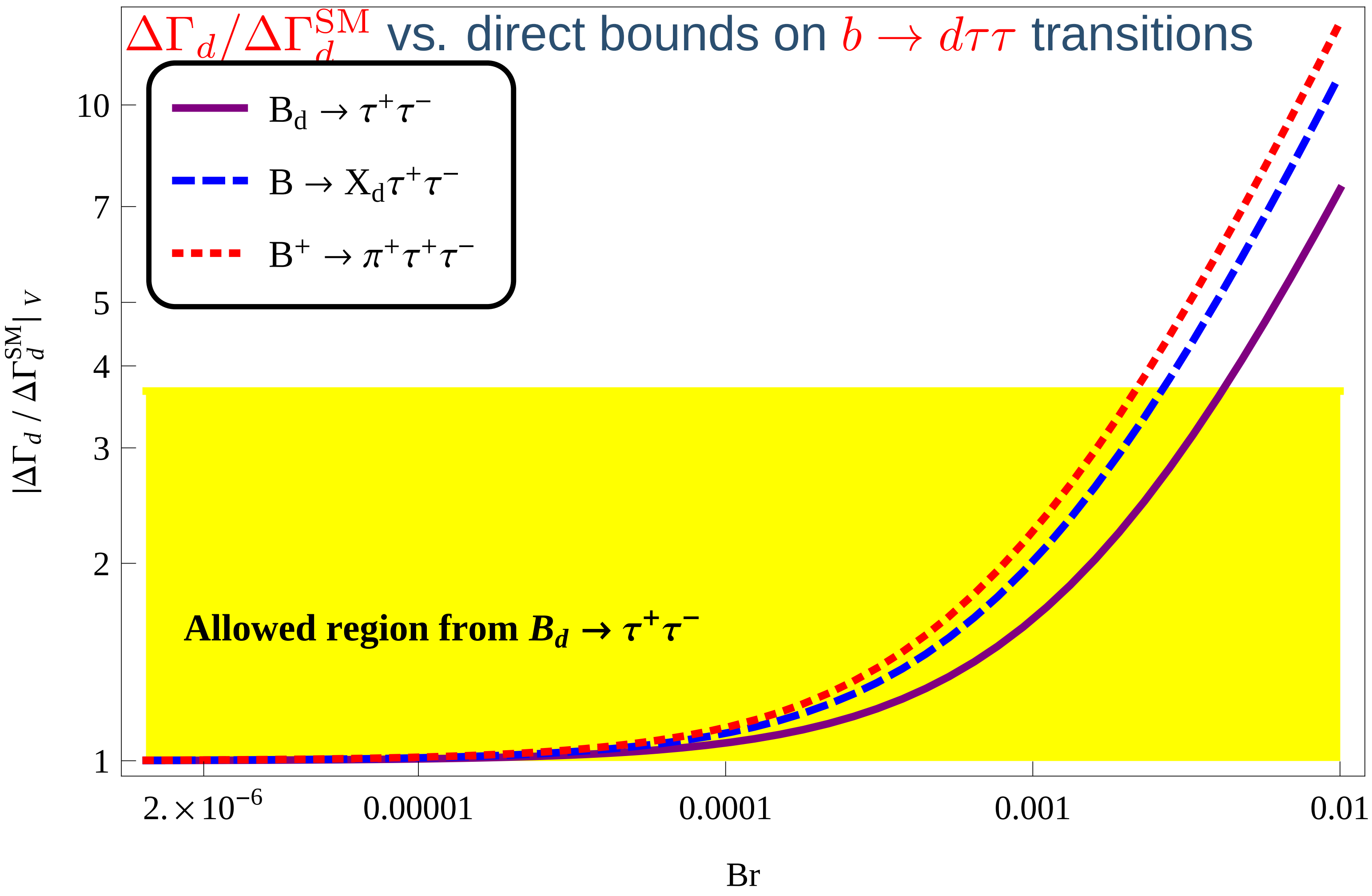
- $b \to d\tau\tau$ can enhance $\Delta\Gamma_d$ and a_{sl}^d. It is constrained by
  - $B_d \to \tau\tau < 4.1 \cdot 10^{-3}$ **direct** from **BaBar 2006**
  - $B \to X_d\tau\tau < 2.7\%$ **indirect from** $\tau(B_s)/\tau(B_d)$
  - $B^+ \to \pi^+\tau\tau < 2.7\%$ **indirect from** $\tau(B_s)/\tau(B_d)$

  $\Rightarrow$ Enhancement of up to **270**$\%$ in $\Delta\Gamma_d$ possible

  This might solve the dimuon asymmetry! $\Rightarrow$ **Improve bounds on** $b \to d\tau\tau$**!**

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

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

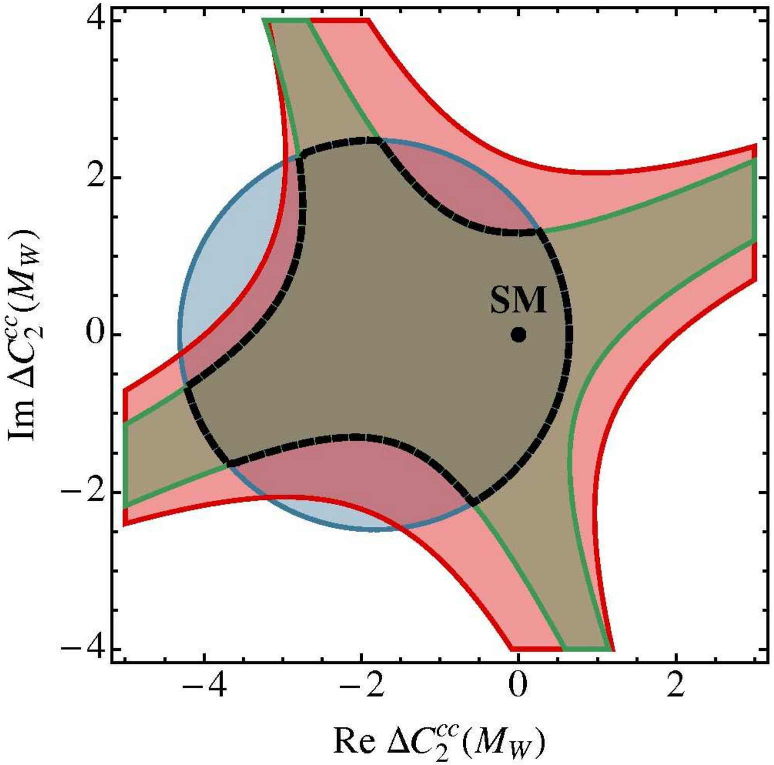


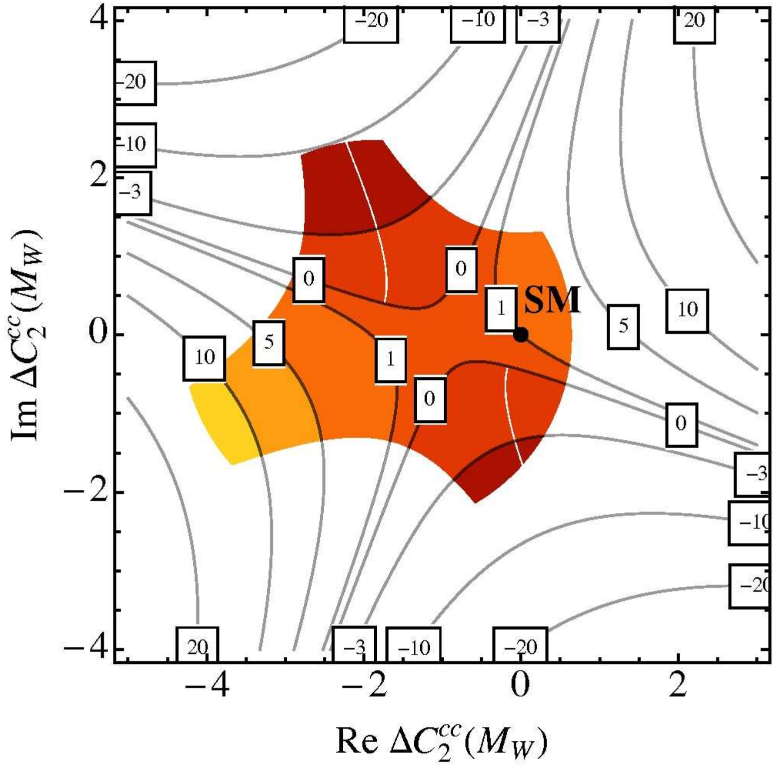
Bobeth, Haisch, AL, Pecjak, Tetlalmatzi-Xolocotz, 2014

New physics in $\Delta\Gamma_d$

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

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





Constraints from $B \to \pi\pi, \rho\pi, \rho\rho, D^*\pi$, $B \to X_d\gamma$, $\sin 2\beta$ 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

$$O = |A_1 + A_2|^2 = |A_1|^2 + |A_2|^2 + 2Re\left(A_1 A_2^*\right) \to |A_1|^2 + |A_2|^2 + 2(1-\zeta) Re\left(A_1 A_2^*\right)$$

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**

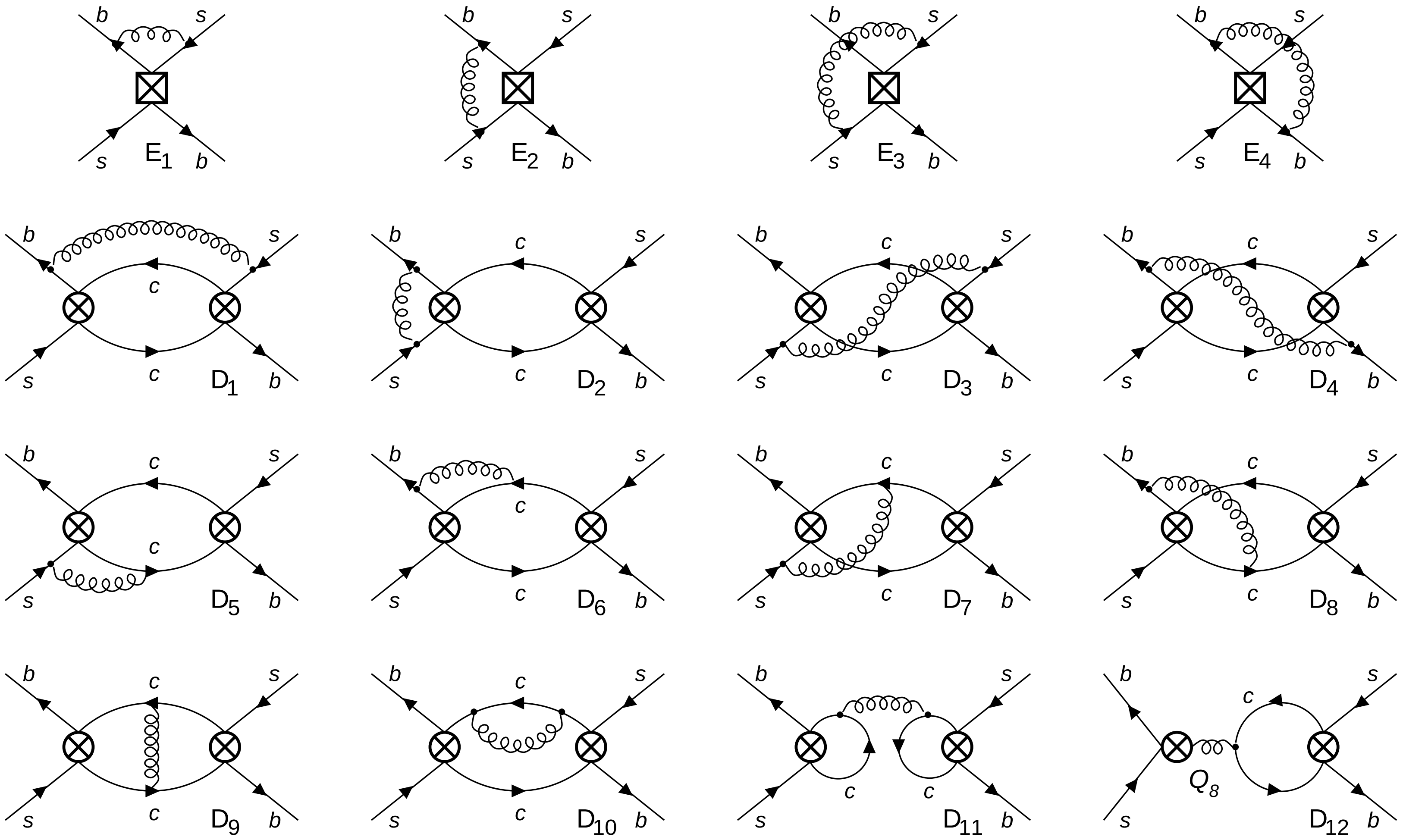
$$\zeta = -0.26^{+0.30}_{-0.28}$$

δR	$\pm 10\%$	$\pm 5\%$	$\pm 2\%$
$\delta\zeta$	$+45.2\%$ -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

$$
\begin{aligned}
Q &= (\bar{b}_i s_i)_{V-A} \cdot (\bar{b}_j s_j)_{V-A} \\
\tilde{Q}_s &= (\bar{b}_i s_j)_{S-P} \cdot (\bar{b}_i s_j)_{S-P} \\
\langle \bar{B}_s | Q | B_s \rangle &= \frac{8}{3} f_{B_S}^2 M_{B_S}^2 B \\
\langle \bar{B}_s | \tilde{Q}_S | B_s \rangle &= \frac{1}{3} f_{B_S}^2 M_{B_S}^2 \tilde{B}'_S = \frac{1}{3} f_{B_S}^2 M_{B_S}^2 \frac{M_{B_S}^2}{(\bar{m}_b + \bar{m}_s)^2} \tilde{B}_S
\end{aligned}
$$

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

$$
\begin{aligned}
R_0 &= Q_s + \tilde{Q}_S + \frac{1}{2} Q \\
R_1 &= \frac{m_s}{m_b} (\bar{b}_i s_i)_{S-P} (\bar{b}_j s_j)_{S+P} \\
R_2 &= \frac{1}{m_b^2} (\bar{b}_i \overleftarrow{D}_\rho \gamma^\mu (1-\gamma_5) D^\rho s_i)(\bar{b}_j \gamma_\mu (1-\gamma_5) s_j) \\
R_3 &= \frac{1}{m_b^2} (\bar{b}_i \overleftarrow{D}_\rho (1-\gamma_5) D^\rho s_i)(\bar{b}_j (1-\gamma_5) s_j) \\
\tilde{R}_i &= \tilde{R}_i(R_j)
\end{aligned}
$$

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 $\Delta\Gamma_s$

$\Delta\Gamma_s^{\mathrm{SM}}$	2011	2006
Central Value	$0.087\,\mathrm{ps}^{-1}$	$0.096\,\mathrm{ps}^{-1}$
$\delta(\mathcal{B}_{\widetilde{R}_2})$	17.2%	15.7%
$\delta(f_{B_s})$	13.2%	33.4%
$\delta(\mu)$	7.8%	13.7%
$\delta(\widetilde{\mathcal{B}}_{S,B_s})$	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** Γ_{12}
- α_s/m_b **corrections for** Γ_{12}
- α_s^2 **corrections for** Γ_{12} **first step: Asatrian, Hovhannisyan, Yeghiazaryan, arXiv:1210.7939**

Effective B_s lifetimes

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

with

$$\mathcal{A}^f_{\Delta\Gamma_q} = -\frac{2\mathrm{Re}(\lambda_f)}{1+|\lambda_f|^2}\,, \qquad \lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}\,, \qquad y_q = \frac{\Delta\Gamma_q}{2\Gamma_q}$$

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

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

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

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

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

- **CP-even** τ_L

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

- **CP-odd** τ_H

$$\tau(B_s \to \psi f_0) = 1.656(33) \text{ ps} \qquad \textbf{HFAG2014}$$

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 ± 0.054	0.955 ± 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: $\Delta\Gamma_d, B \to X\tau\tau, \tau(B_s)/\tau(B_d), a_{sl}, R, C_{1,2}...$

- **Life becomes harder: higher precision in experiment and theory needed**
  - **Non-perturbative parameters - lattice - current limitation of progress in HQE**
  - **Higher order perturbative corrections**
  - **Experimentally more difficult observables**
  - **Alternative non-perturbative methods (LCSR,...)**
  - **Take penguins into account**