τ_{B_s} and $\Delta\Gamma_s$

Alexander Lenz

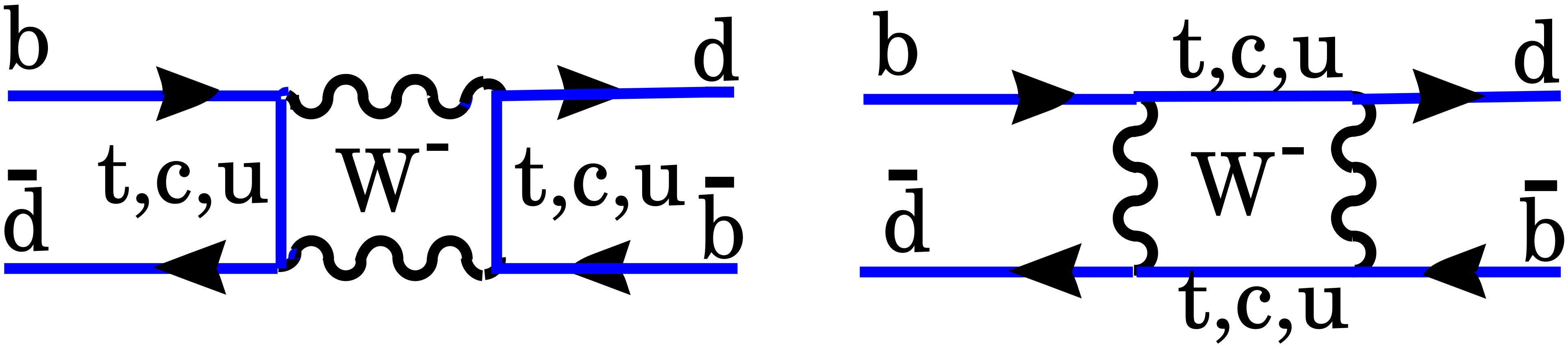
CERN, Theory Division

Mixing I

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

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

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



$\Rightarrow$ **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 $|p|^2 + |q|^2 = 1$

Mixing II

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

- **Mass difference:** $\Delta M := M_H - M_L = 2|M_{12}| \left(1 - \frac{1}{8}\frac{|\Gamma_{12}|^2}{|M_{12}|^2}\sin^2\phi + ...\right)$
  $|M_{12}|$: 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 $B_q \to Xl\nu$ (*semileptonic*)

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

The Mass Difference ΔM

Calculating the box diagram with an internal top-quark yields

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

(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)

Theory 1102.4274 vs. Experiment : HFAG 12

$\Delta M_d = 0.543 \pm 0.091\ ps^{-1}$	$\Delta M_d = 0.507 \pm 0.004\ ps^{-1}$ ALEPH, CDF, D0, DELPHI, L3, OPAL, BABAR, BELLE, ARGUS, CLEO
$\Delta M_s = 17.30 \pm 2.6\ ps^{-1}$	$\Delta M_s = 17.69 \pm 0.08\ ps^{-1}$ CDF, D0, LHCb

Important bounds on the unitarity triangle and new physics

The Mass Difference ΔM

Crucial dependence on non-perturbative parameters!
2011 $f_{B_s} = 231 \pm 15$ MeV used.

Newer Results:

- 1110.4510 - HPQCD: $f_{B_s} = 225 \pm 4$ MeV
- 1112.3051 - Fermilab: $f_{B_s} = 242 \pm 9.5$ MeV

$$\Delta M_s = 17.3 \pm 2.6 \, ps^{-1} \qquad \Delta M_s^{\text{Exp.}} = 17.69 \pm 0.08 \, ps^{-1}$$

$$\Delta M_s^{\text{HPQCD}} = 16.4 \pm 0.8 \, ps^{-1}$$

$$\Delta M_s^{\text{Fermilab}} = 19.0 \pm 1.2 \, ps^{-1}$$

Determination of Γ_{12}

Sensitive to real intermediate states $\Rightarrow$ much more complicated than M_{12}

1. OPE I: Integrate out W: like $M_{12} \propto f_B^2 B$
2. OPE II: Heavy quark expansion $\Rightarrow \Gamma_i^{(j)} \propto f_B^2 \sum C_k B_K$

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

1996: Beneke, Buchalla, Dunietz

1998: Beneke, Buchalla, Greub, A.L., Nierste

2003: Ciuchini, Franco, Lubicz, Mescia, Tarantino; Beneke, Buchalla, A.L., Nierste

2006: A.L., Nierste

2007: Badin, Gabbiani, Petrov

HQE under attack!

OPE II might be questionable - relies on quark hadron duality

- Mid 90's: Missing Charm puzzle $n_c^{\text{Exp.}} < n_c^{\text{SM}}$, semi leptonic branching ratio
- Mid 90's: Λ_b lifetime is too short
- before 2003: $\tau_{B_s}/\tau_{B_d} \approx 0.94 \neq 1$
- 2010/2011: Di-muon asymmetry too large

Theoretical "tests" for HQE

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

$\Rightarrow$ test reliability of OPE II via lifetimes (no NP effects expected) "directions", to test convergence

HQE under attack!

Theoretical "tests" for HQE

- Test convergence

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

- Test Lifetimes

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

2002: Beneke, Buchalla, Greub, A.L., Nierste; Franco, Lubicz, Mescia, Tarantino

2004: Greub, A.L., Nierste; 2008 A.L.

$$\left[\frac{\tau(B^+)}{\tau(B_d^0)}\right]_{\text{LO,NLO,HFAG12}} = 1.047 \pm 0.049 \leftrightarrow 1.044 \pm 0.024 \leftrightarrow 1.079 \pm 0.007$$

Lifetimes: τ_{B^+}/τ_{B_d}

$$\frac{\tau_{B^+}}{\tau_{B_d}} - 1 = 0.0324 \left(\frac{f_B}{200\text{MeV}}\right)^2 \quad [(1.0 \pm 0.2) B_1 + (0.1 \pm 0.1) B_2$$
$$- \quad (17.8 \pm 0.9)\epsilon_1 + (3.9 \pm 0.2)\epsilon_2 - 0.26]$$

with non-perturbative input from Becirevic hep-ph/0110124

$$\begin{aligned} B_1 &= 1.10 \pm 0.20 \\ B_2 &= 0.79 \pm 0.10 \\ \epsilon_1 &= -0.02 \pm 0.02 \\ \epsilon_2 &= 0.03 \pm 0.01 \end{aligned}$$

Update urgently needed!

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OPE II might be questionable - relies on quark hadron duality

- 2012: $n_c^{2006\mathrm{BaBar}} = 1.20 \pm 0.06$ vs. $n_c^{\mathrm{SM}} = 1.20 \pm 0.04$
  Eberhardt, Krinner, A.L., Rauh in prep.
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- HFAG '03 $\tau_{\Lambda_b} = 1.229 \pm 0.080$ ps^{-1} $\longrightarrow$ HFAG '12 $\tau_{\Lambda_b} = 1.425 \pm 0.032$ ps^{-1}
  Shift by 2.5σ $\Rightarrow$Eagerly waiting for new LHCb results!!!
  In agreement with theory, e.g. Tarantino 2007
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The B_s lifetime

Recent fits from $B_s \to \psi\phi$ vs SM A.L., Nierste 2011

$$\tau_{B_s}^{\rm LHCb2012} = 1.520 \pm 0.020 \text{ ps}$$
$$\tau_{B_s}^{\rm CDF2012} = 1.528 \pm 0.021 \text{ ps}$$
$$\tau_{B_s}^{\rm D02011} = 1.443 \pm 0.038 \text{ ps}$$
$$\Rightarrow \frac{\tau_{B_s}}{\tau_{B_d}}^{\rm LHCb2012} = 1.001 \pm 0.014 \qquad \frac{\tau_{B_s}}{\tau_{B_d}}^{\rm SM} = 0.996 ... 1.000$$

- 0.940 ± 0.014 would have been a desaster for SM = may be NP :-)
- Update of effective lifetimes (LHCb2012, CDF, HFAG 2012)
  Fleischer et al used 1011.1096, 1109.1112, 1109.5115: τ_{B_s} = 1.477 ps

	Exp.	SM-old	SM-new
$\tau^{\rm Eff}(K^+K^-)$	1.468 ± 0.046	1.390 ± 0.032	1.43 ± 0.03
$\tau^{\rm Eff}(\psi f_0)$	1.70 ± 0.12	1.582 ± 0.036	1.63 ± 0.03
$\tau^{\rm FS}$	1.463 ± 0.032	$---$	1.54 ± 0.03

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- **Moriond 2012 LHCb:** $\tau_{B_s}/\tau_{B_d} = 1.001 \pm 0.014$
- 2010/2011: Di-muon asymmetry too large — Test Γ_{12} with $\Delta\Gamma_s$!

Theory arguments for HQE

$\Rightarrow$ calculate corrections in all possible “directions”, to test convergence
$\Rightarrow$ Γ_{12} seems to be ok!

$\Rightarrow$ test reliability of OPE II via lifetimes (no NP effects expected) “directions”, to test convergence
$\Rightarrow$ $\tau(B^+)/\tau(B_d)$ Experiment and theory agree within hadronic uncertainties

Finally $\Delta\Gamma_s$ is measured! (naive: 6.1σ)

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

Crucial dependence on non-perturbative parameters!

2011 $f_{B_s} = 231 \pm 15$ MeV used in A.L., Nierste 2011

Newer Results:

- 1110.4510 - HPQCD: $f_{B_s} = 225 \pm 4$ MeV $\Rightarrow \Delta\Gamma_s = (0.083 \pm 0.017)\,\text{ps}^{-1}$
- 1112.3051 - Fermilab: $f_{B_s} = 242 \pm 9.5$ MeV $\Rightarrow \Delta\Gamma_s = (0.095 \pm 0.021)\,\text{ps}^{-1}$
- 1201.3956 - chiral QM: $f_{B_s} = 262 \pm ?$ MeV $\Rightarrow \Delta\Gamma_s = (0.112 \pm ?)\,\text{ps}^{-1}$

LHCb from $B_s \to J/\psi\phi$

Moriond 2012 $\Delta\Gamma_s = (0.116 \pm 0.019)\,\text{ps}^{-1} \quad \Rightarrow \quad \frac{\Delta\Gamma_s^{Exp}}{\Delta\Gamma_s^{SM}} = 1.33 \pm 0.39$

- CDF 9.6fb^{-1}: Note 10778: $\Delta\Gamma_s = (0.068 \pm 0.027)\,\text{ps}^{-1}$
- D0 8.0fb^{-1}: 1109.3166: $\Delta\Gamma_s = (0.163 \pm 0.065)\,\text{ps}^{-1}$
- HFAG 2012: $\Delta\Gamma_s = (0.100 \pm 0.014)\,\text{ps}^{-1} \Rightarrow \Delta\Gamma_s^{Exp}/\Delta\Gamma_s^{SM} = 1.15 \pm 0.32$

Finally $\Delta\Gamma_s$ is measured! (naive: 6.1σ)

Get rid off the dependence on f_{B_s} (No NP in ΔM)

$$\frac{\Delta\Gamma_s}{\Delta M_s} = 10^{-4} \cdot \left[46.2 + 10.6 \frac{\tilde{B}'_S}{B} - \left(13.2 \frac{B_{\tilde{R}_2}}{B} - 2.5 \frac{B_{R_0}}{B} + 1.2 \frac{B_R}{B}\right)\right]$$
$$= 0.0050 \pm 0.0010$$

HQE vs. Experiment (HFAG 2012)

$$\left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^{\rm Exp} / \left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^{\rm SM} = 1.13 \pm 0.28$$

HQE works also for Γ_{12}!

How precise does it work? 30%? 10%?

Still more accurate data needed! **TeVatron, LHCb, Super-B(elle)**

$\Delta\Gamma_s^{\rm CP}/\Gamma_s = 2Br(B_s \to D_s^{(*)+} + D_s^{(*)-})$?

- 1993 Aleksan; Le Yaouanc, Olivre, Pene, Raynal:
  The above equation holds in the limit: $m_c \to \infty; m_b - 2m_c \to 0; N_c \to \infty$
  Corresponds to negligible 3-body final state contributions to Γ_{12}^s

$$\frac{\Delta\Gamma_s}{\Gamma_s} \propto \mathcal{O}(0.15)$$

- 1107.4325 Chua, Hou, Shen Reanalysis of the exclusive approach
  - 2-body final states contribute 0.100 ± 0.030 to $\Delta\Gamma/\Gamma$
    Aleksan et al were lucky...
  - 3-body final states contribute about 0.06...0.08
    This is comparable to 2-body final states! $\Rightarrow$ bad approximation $\Rightarrow$ test exp.

We strongly discourage from the inclusion of $Br(Bs \to D^{(*)+} + D^{(*)-})$ *in averages with* $\Delta\Gamma_s$ *determined from clean methods.*

A.L., Nierste; hep-ph/0612167

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

SM predictions: A.L., U. Nierste, 1102.4274; A.L. 1108.1218

$$
\begin{aligned}
a_{fs}^s &= (1.9 \pm 0.3) \cdot 10^{-5} & \phi_s &= 0.22^\circ \pm 0.06^\circ \\
a_{fs}^d &= -(4.1 \pm 0.6) \cdot 10^{-4} & \phi_d &= -4.3^\circ \pm 1.4^\circ \\
A_{sl}^b = 0.406 a_{sl}^s &+ 0.594 a_{sl}^d & = & (-2.3 \pm 0.4) \cdot 10^{-4}
\end{aligned}
$$

Experimental bounds

$a_{fs}^s = (-1050 \pm 640) \cdot 10^{-5}$ (HFAG 12)

$\phi_s = -51.6^\circ \pm 12^\circ$ (A.L., Nierste, CKMfitter, 1008.1593)

$ = -0.1^\circ \pm 5.0^\circ$ LHCb Moriond 2012

$a_{fs}^d = -(33 \pm 33) \cdot 10^{-4}$ (HFAG 12)

$\frac{\Delta\Gamma_d}{\Gamma_d} = (-17 \pm 21) \cdot 10^{-3}$ (Belle EPS 2011)

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

$A_{sl}^b(Exp.)/A_{sl}^b(Theory) = \mathbf{34}$ $\quad 3.9 - \sigma$**-effect**

New Physics in B-Mixing I

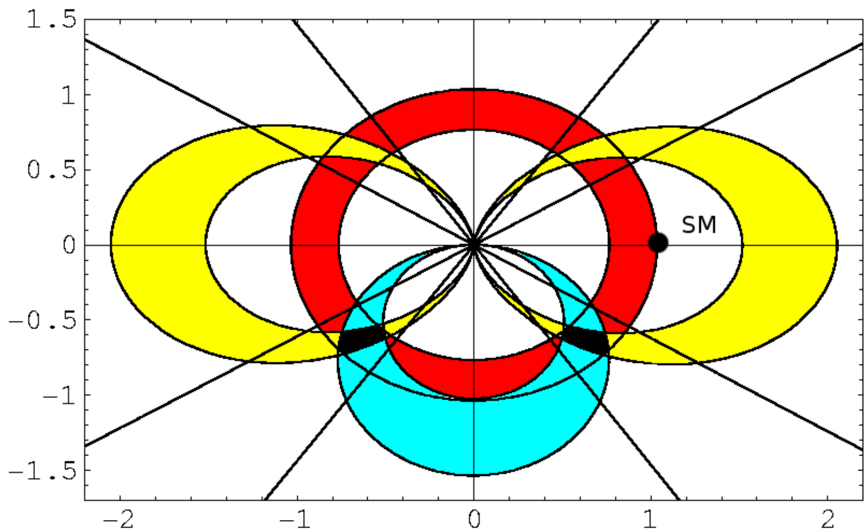
$$\Gamma_{12,s} = \Gamma_{12,s}^{\rm SM}\,, \qquad M_{12,s} = M_{12,s}^{\rm SM} \cdot \Delta_s\,; \qquad \Delta_s = |\Delta_s| e^{i\phi_s^\Delta}$$

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

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

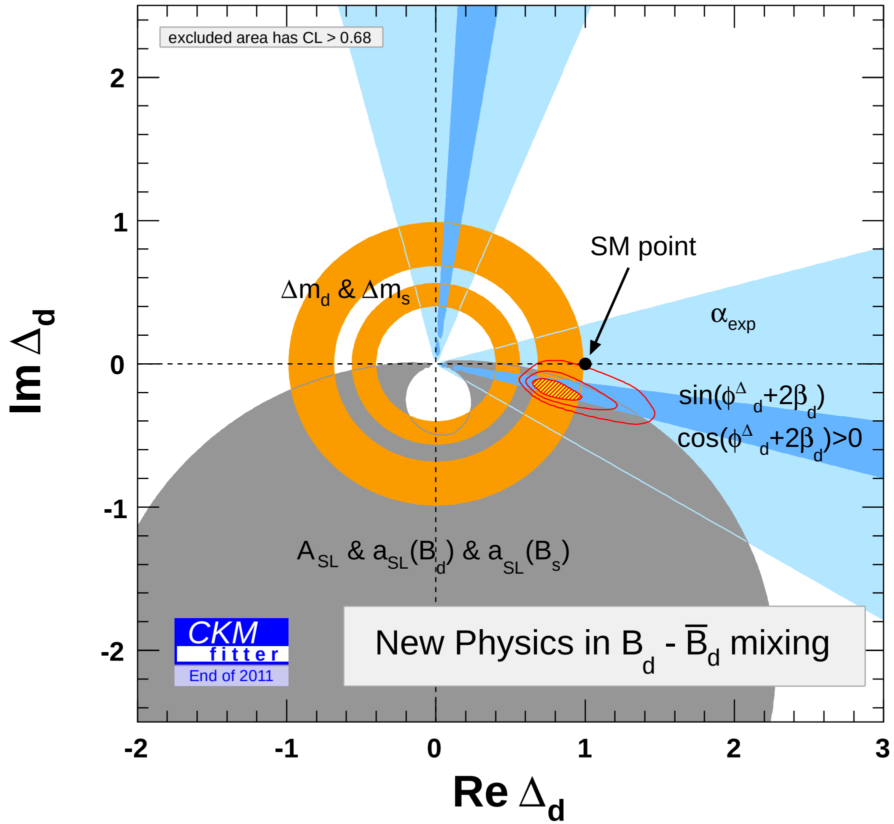
$$\sin(\phi_s^{\rm SM}) \approx 1/240$$

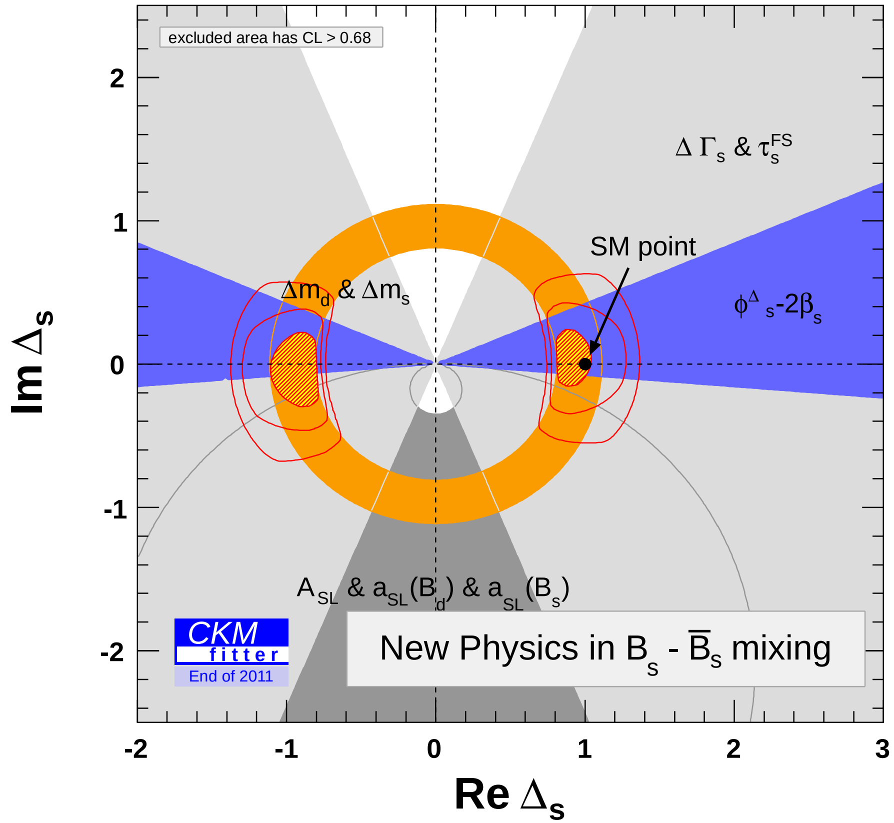
For $|\Delta_s| = 0.9$ and $\phi_s^\Delta = -\pi/4$ one gets the following bounds in the **complex Δ-plane**:



New Physics in B-Mixing II

Combine all data till end of 2011 and neglect penguins
fit of Δ_d and Δ_s 1203.0238 (update of 1008.1593) soon v2!





- Fits not so good anymore (LHCb vs. Dzero)
- $B \to \tau\nu$ vs. $\sin 2\beta$ solved with ϕ_d^Δ — No tension for ϵ_K

The dimuon asymmetry

The central value of the diμasymmetry is larger than *theoretically* possible!

$$A_{sl}^{Max.} \approx (0.594 \pm 0.022)(5.4 \pm 1.0) \cdot 10^{-3} \frac{\sin(\phi_d^{SM} + \phi_d^{\Delta})}{|\Delta_d|}$$

$$+ (0.406 \pm 0.022)(5.0 \pm 1.1) \cdot 10^{-3} \frac{\sin(\phi_s^{SM} + \phi_s^{\Delta})}{|\Delta_s|}$$

$$\approx (-3.1; -4.8[1\sigma]) \cdot 10^{-3}$$

$$A_{sl}^{D0} = (-7.8 \pm 2.0) \cdot 10^{-3}$$

A.L. 1108.1218

Possible solutions:

- HQE violated by $\mathcal{O}(200\% - 3300\%)$ now excluded!
- Huge new physics in Γ_{12}? - Not possible! Violates all kinds of bounds, e.g. $\tau_{B_s}, B_s \to \tau\tau, n_c, ...$ see talk by Christoph Bobeth
- Contradiction to $B_s \to J/\psi\phi$ from LHCb? - Penguins become important!
- Stat. fluctuation (1.5 σ) of the D0 result? (Actual value is below -4.8 per mille?) Independent measurements of semi leptonic asymmetries needed!

How large are Penguins?

Angular analysis of $B_s \to J/\psi\phi$ at CDF, D0 and LHCb:

$$S_{\psi\phi}^{\rm SM} = 0.0036 \pm 0.002 \to \sin\left(2\beta_s - \phi_s^\Delta - \delta_s^{\rm Peng,SM} - \delta_s^{\rm Peng,NP}\right) = 0.002 \pm 0.087$$

LHCb Moriond 2012

Is this a contraction to the dimuon asymmetry?

Depends on the possible size of penguin contributions

- SM penguin are expected to be very small
  but see also Faller, Fleischer; Mannel 2008
- NP penguins might be larger

But: even small penguin contributions have a sizeable effect!

CKM$^-$: How large are Penguins? II

Many observables in the B_s mixing system:

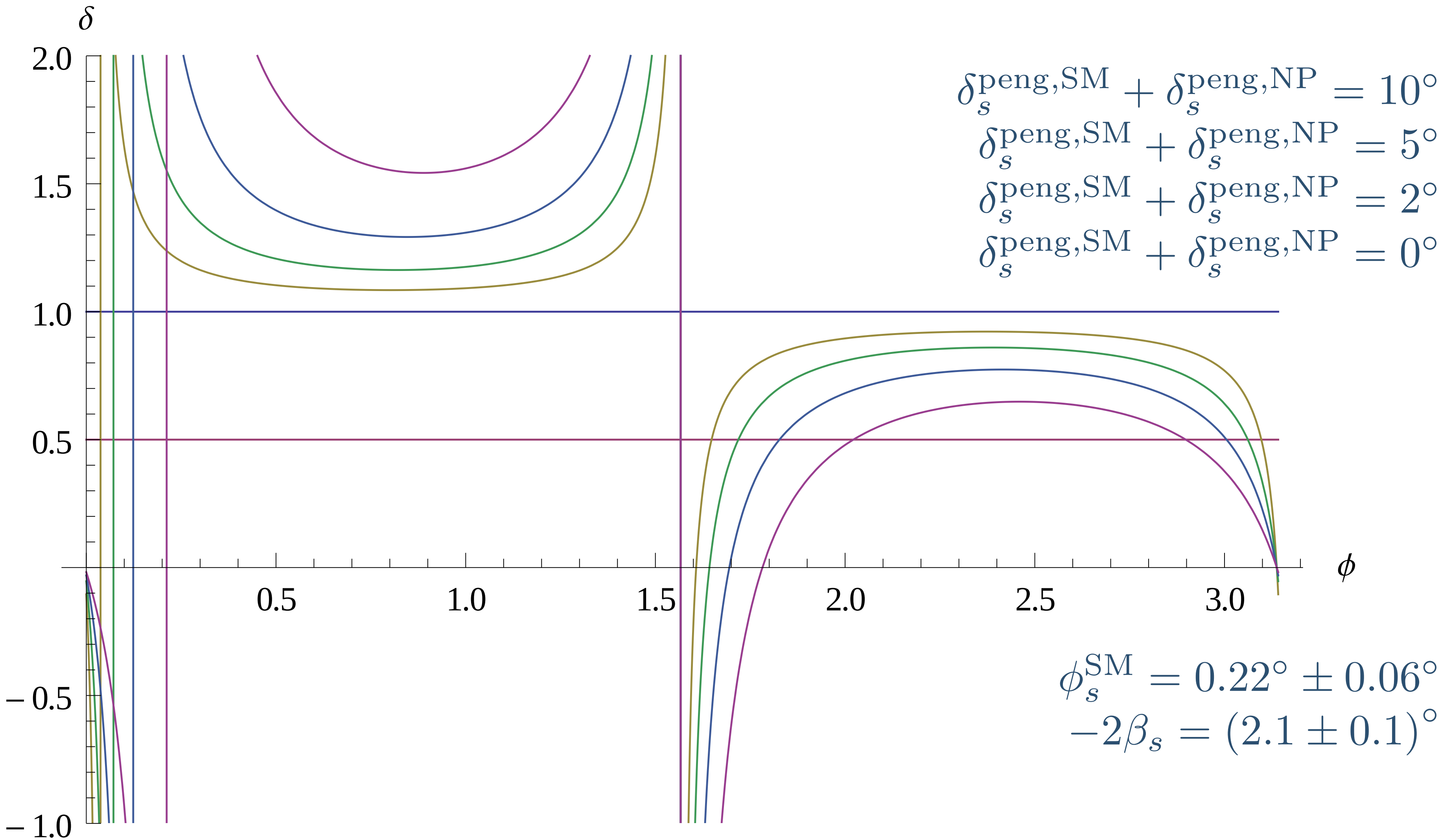
$$a_{sl}^s = -\frac{\Delta\Gamma}{\Delta M}\frac{S_{\psi\phi}}{\sqrt{1-S_{\psi\phi^2}}}\cdot\delta$$

Be aware: $\delta \neq 1$ (A.L. 1106.3200)

$$\delta = \frac{\tan\left(\phi_s^{\rm SM}+\phi_s^{\Delta}\right)}{\tan\left(-2\beta_s^{\rm SM}+\phi_s^{\Delta}+\delta_s^{\rm peng,SM}+\delta_s^{\rm peng,NP}\right)}$$

A “measurement” of δ might give some information about the penguins!

CKM$^-$: How large are Penguins? III



- Above relation can be used to determine $\delta_s^{\text{peng,SM}} + \delta_s^{\text{peng,NP}}$
- To extract ϕ_s^Δ one needs $\Gamma_{12}^{s,\text{SM}}$

A.L. 1106.3200

Conclusion

- First measurement of $\Delta\Gamma_s$!!!
  - Theoretical calculations since 1977
  - Theoretical discussion about quark hadron duality settled!
- HQE works perfectly but how precise is the HQE? 30%, 10%?
  - More precise measurements of lifetimes and $\Delta\Gamma_s$ needed!
  - Matrix elements of 4-quark operators urgently needed!
  - Combination of lattice results - FLAG-2?
- Understand the di-muon asymmetry!
  - HQE violations and NP in Γ_{12} can not do the full job
  - Statistical deviation of the measurement by 1.5σ
  - Experimental cross-check via a_{sl}^d and a_{sl}^s urgently needed
- New physics effects are not huge
  $\Rightarrow$ Control over penguins will become very important!