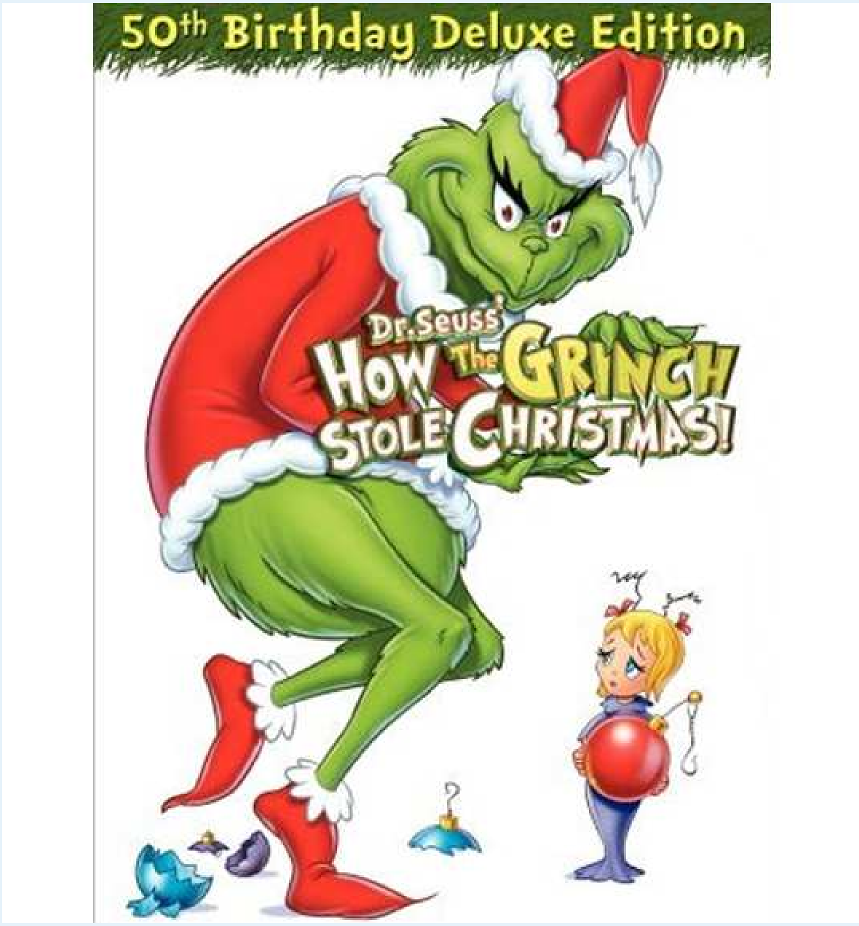
SM predictions for B mixing observables



Alexander Lenz

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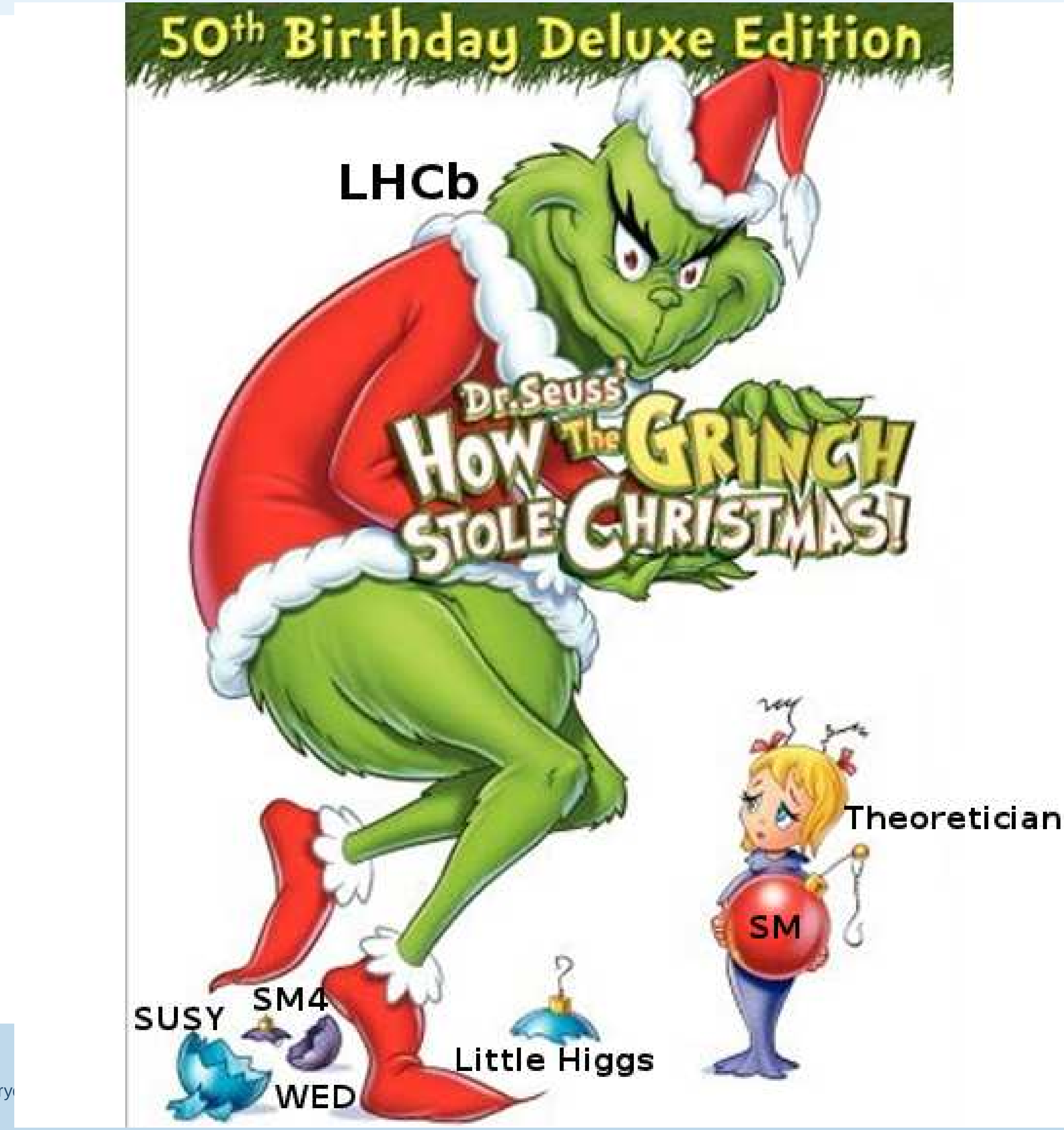
TeVatron gave us many presents, and then ...

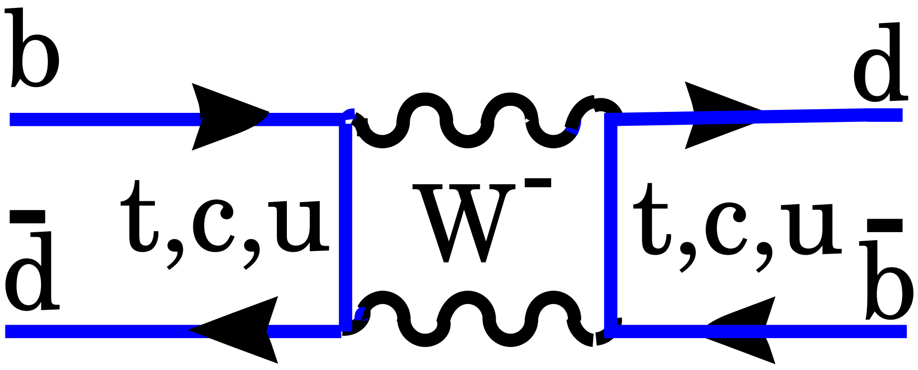


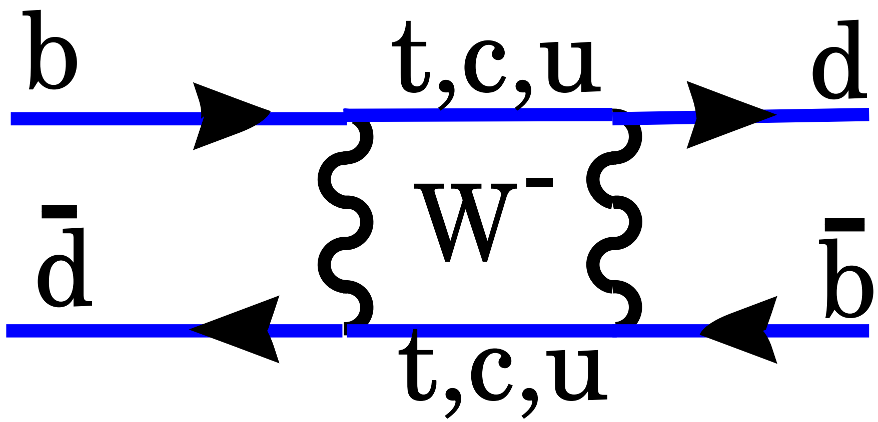
Mixing I

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

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

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





Mixing II

Mixing is a macroscopic quantum effect!

It was observed in

- K^0-system: 1950s (see text books, regeneration...)
- B_d-system: 1986
- B_s-system: 2006
- D^0-system: 2007

Strongly suppressed in the SM (due to virtual top-quarks)
New physics effects might be of comparable size

?Is QCD under control?

Mixing III

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

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

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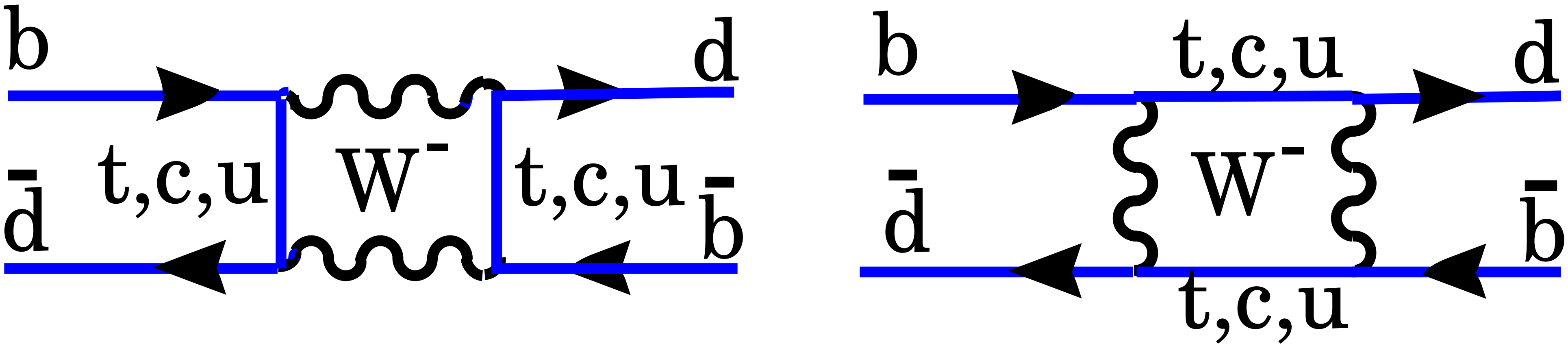

$\Rightarrow$ **off-diagonal elements** in $\hat{M}$, $\hat{\Gamma}$: M_{12}, Γ_{12} (complex)
Diagonalization of $\hat{M}$, $\hat{\Gamma}$ gives the physical eigenstates B_H and B_L with the masses M_H, M_L and the decay rates Γ_H, Γ_L

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 IV

$|M_{12}|$, $|\Gamma_{12}|$ 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 11

Theory	Experiment
$\Delta M_d = 0.543 \pm 0.091\, ps^{-1}$	$\Delta M_d = 0.507 \pm 0.004\, ps^{-1}$ ALEPH, CDF, D0, DELPHI, L3, OPAL, BABAR, BELLE, ARGUS, CLEO
$\Delta M_s = 17.30 \pm 2.6\, ps^{-1}$	$\Delta M_s = 17.70 \pm 0.12\, ps^{-1}$ CDF, D0, LHCb

Important bounds on the unitarity triangle and new physics

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

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

HQE under attack!

OPE II might be questionable - relies on quark hadron duality

- Mid 90's: Missing Charm puzzle $n_c^{\mathrm{Exp.}} < n_c^{\mathrm{SM}}$, 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

Theory arguments for HQE

$\Rightarrow$ calculate corrections in all possible "directions", to test convergence
$\Rightarrow \Gamma_{12}$ 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

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  Shift by 4σ $\Rightarrow$Eagerly waiting for new LHCb results!!!
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The B_s lifetime

Moriond 2012 LHCb vs SM A.L., Nierste 2011

$$\frac{\tau_{B_s}}{\tau_{B_d}}^{\text{Exp}} = 1.001 \pm 0.014 \qquad \frac{\tau_{B_s}}{\tau_{B_d}}^{\text{SM}} = 0.996 \ldots 1.000$$

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

	Exp.	SM-old	SM-new
$\tau^{\text{Eff}}(K^+K^-)$	1.44 ± 0.10	1.390 ± 0.032	1.43 ± 0.03
$\tau^{\text{Eff}}(\psi f_0)$	1.70 ± 0.12	1.582 ± 0.036	1.63 ± 0.03
τ^{FS}	1.417 ± 0.042	$---$	1.54 ± 0.03

HQE under attack!

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- 2010/2011: Di-muon asymmetry too large — Test Γ_{12} with $\Delta\Gamma_s$!

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$\Delta\Gamma_s$ in NLO-QCD I

A brief history of theory predictions

'81... Hagelin; Buras et al.;...	$\Delta\Gamma \propto \mathcal{O}\left(0.15 \text{ ps}^{-1}\right)$
'93 Aleksan et al.; ...	$\Delta\Gamma \propto \mathcal{O}\left(0.10 \text{ ps}^{-1}\right)$
'96 Beneke, Buchalla, Dunietz	$\Delta\Gamma_s = \left(0.11^{+0.07}_{-0.06}\right) \text{ ps}^{-1}$
'00 Beneke, A.L.	$\Delta\Gamma_s = (0.06 \pm 0.03) \text{ ps}^{-1}$
'03 Ciuchini, et al	$\Delta\Gamma_s = (0.050 \pm 0.016) \text{ ps}^{-1}$
'06 A.L., Nierste	$\Delta\Gamma_s = (0.096 \pm 0.036) \text{ ps}^{-1}$
'11 A.L., Nierste	$\Delta\Gamma_s = (0.087 \pm 0.021) \text{ ps}^{-1}$

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 $\Rightarrow \Delta\Gamma_s = (0.083 \pm 0.017) \text{ ps}^{-1}$
- 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 $\Rightarrow \Delta\Gamma_s = (0.112 \pm ?) \text{ ps}^{-1}$

$\Delta\Gamma_s$ in NLO-QCD II

Improvement in theoretical accuracy

$\Delta\Gamma_s^{\mathrm{SM}}$	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%

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

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

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

$$\text{LP 2011 } \Delta\Gamma_s = (0.123 \pm 0.031)\,\text{ps}^{-1} \Rightarrow \frac{\Delta\Gamma_s^{\rm Exp}}{\Delta\Gamma_s^{\rm SM}} = 1.41 \pm 0.50$$

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

- D0 8fb^{-1} 1109.3166: $\Delta\Gamma_s = (0.163 \pm 0.065)\,\text{ps}^{-1}$
- CDF 9.6fb^{-1}: Talk by G. Borissov $\Delta\Gamma_s < \Delta\Gamma^{\rm SM}$

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

$$\left(\frac{\Delta\Gamma_s}{\Delta M_s} \right)^{\text{Exp}} / \left(\frac{\Delta\Gamma_s}{\Delta M_s} \right)^{\text{SM}} = 1.30 \pm 0.34$$

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

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

Experimental bounds

$$a_{fs}^s = (-1150 \pm 610) \cdot 10^{-5}$$ (HFAG 11)

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

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

$$a_{fs}^d = -(49 \pm 38) \cdot 10^{-4}$$ (HFAG 11)

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

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

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

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

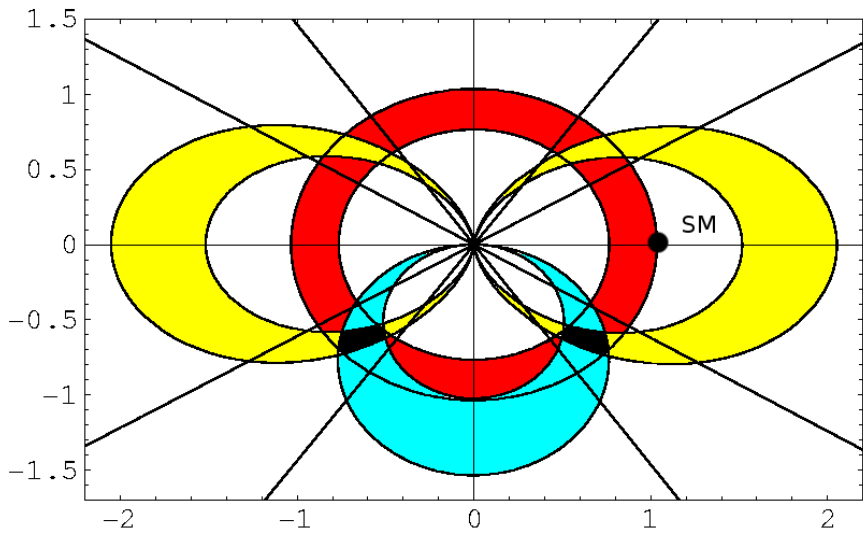
$$\Delta \Gamma_s = 2|\Gamma_{12,s}| \cdot \cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)$$

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

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

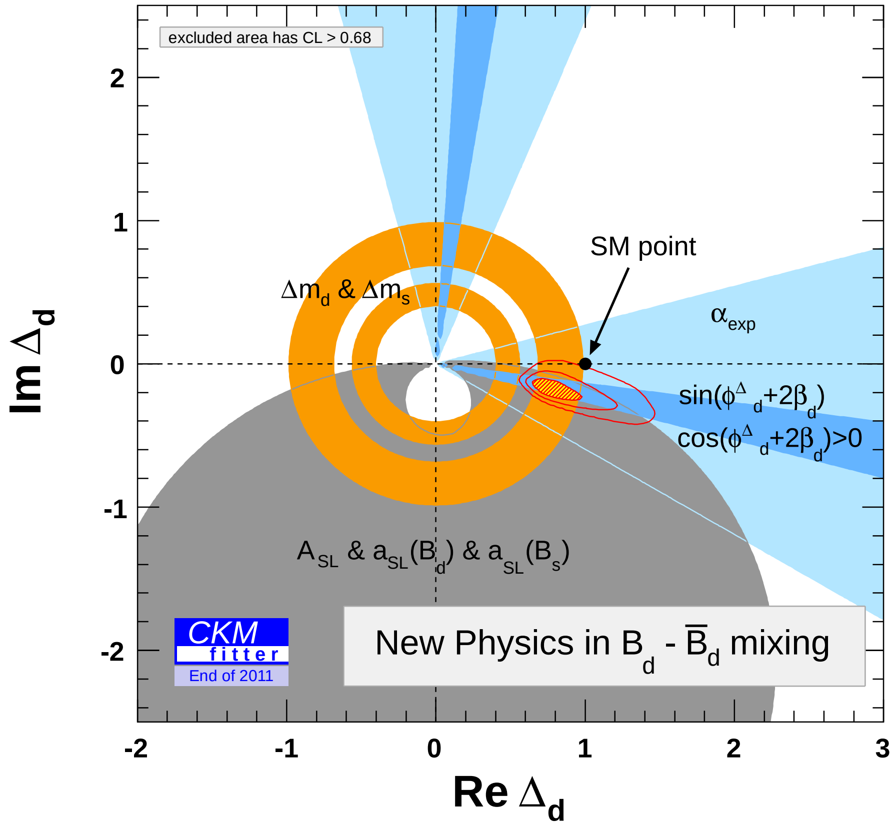
$$\sin(\phi_s^{\rm SM}) \approx 1/240$$

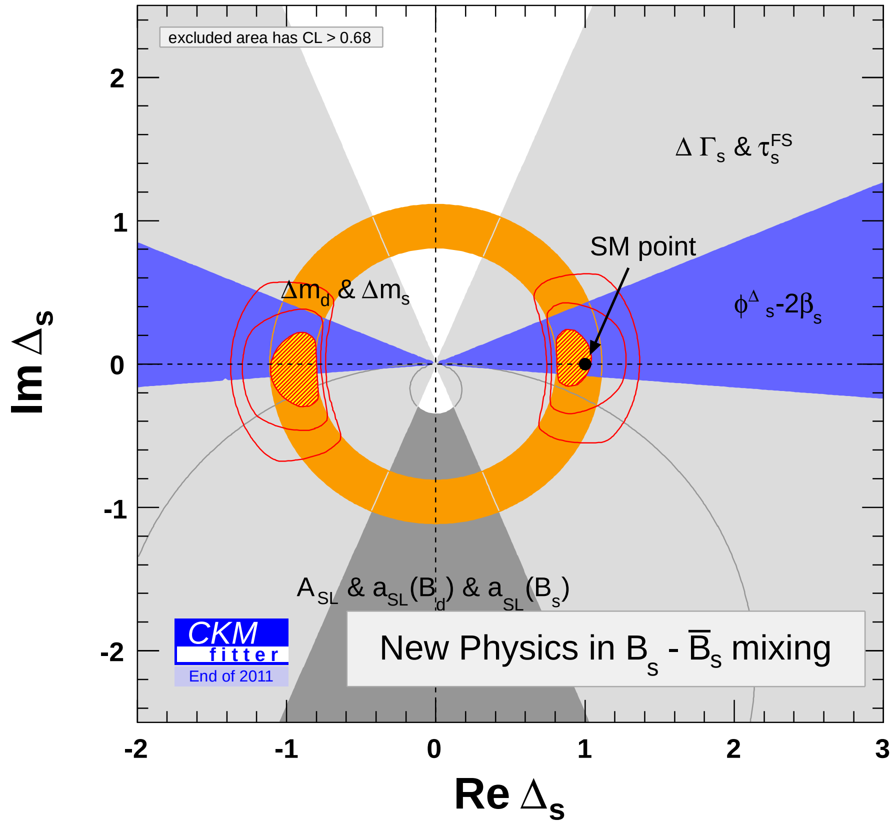
For $|\Delta_s| = 0.9$ and $\phi_s^\Delta = -\pi/4$ one gets the following bounds in the **complex Δ-plane**:



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!

$$
\begin{aligned}
A_{sl}^{Max.} &\approx (0.594 \pm 0.022)(5.4 \pm 1.0) \cdot 10^{-3} \frac{\sin(\phi_d^{SM} + \phi_d^{\Delta})}{|\Delta_d|} \\
&+ (0.406 \pm 0.022)(5.0 \pm 1.1) \cdot 10^{-3} \frac{\sin(\phi_s^{SM} + \phi_s^{\Delta})}{|\Delta_s|} \\
&\approx (-3.1; -4.8[1\sigma]; -9.0[3\sigma]) \cdot 10^{-3} \\
A_{sl}^{D0} &= (-7.8 \pm 2.0) \cdot 10^{-3}
\end{aligned}
$$

A.L. 1108.1218

Possible solutions:

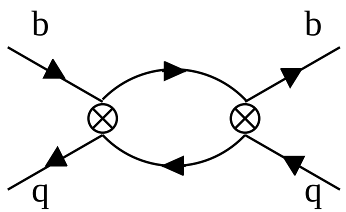
- HQE violated by $\mathcal{O}(200\% - 3300\%)$ now excluded!
- Huge new physics in Γ_{12}? - see talk by Uli Haisch
- Contradiction to $B_s \to J/\psi\phi$ from LHCb? - Penguins
- Stat. fluctuation (1.5 σ) of the D0 result? (Actual value is below -4.8 per mille?)
  Independent measurements of semi leptonic asymmetries needed!

?New physics in Γ_{12}?

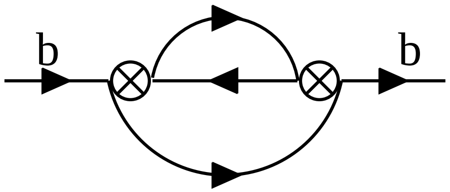
- Large ($\mathcal{O}(200 - 3400\%)$ NP effects in Γ_{12}?

Why not seen somewhere else?

A new operator $bs \to X$ with $M_x < M_B$ contributes not only to a_{sl}^s but also to many more observables, e.g.:

- 

$$\Gamma_3 \Rightarrow \begin{cases} \tau(B_s)/\tau(B_d) \\ \Delta\Gamma_s \end{cases}$$

- 

$$\Gamma_0 \Rightarrow \begin{cases} \tau(B_x) \\ B_{sl} \\ Br(b \to s \text{ no charm}) \end{cases}$$

- ...
- A promising candidate for X seems to be $\tau^+ + \tau^-$ -> Uli Haisch.

?New physics in Γ_{12}?

- **Missing charm puzzle**, e.g.

  Bigi et al '94; Bagan et al. '94; Falk, Wise, Dunietz '95, Neubert '97... A.L. ,hep-ph/0011258

  Look at inclusive b-decay into 0, 1, 2 c-quarks

  Define $r(x \text{ charm}) := \frac{\Gamma(\text{b}\to\text{x charm})}{\Gamma_{\text{sl}}}$: $m_b^5 V_{cb}^2$ cancels; Γ_{sl} seems safe

  The average number of charm quarks per b-decay reads

$$
\begin{aligned}
n_c &= 0 + \left[r(1c) + 2r(2c)\right] B_{sl}^{Exp.} \\
&= 1 + \left[r(2c) - r(0c)\right] B_{sl}^{Exp.} \\
&= 2 - \left[r(1c) + 2r(0c)\right] B_{sl}^{Exp.}
\end{aligned}
$$

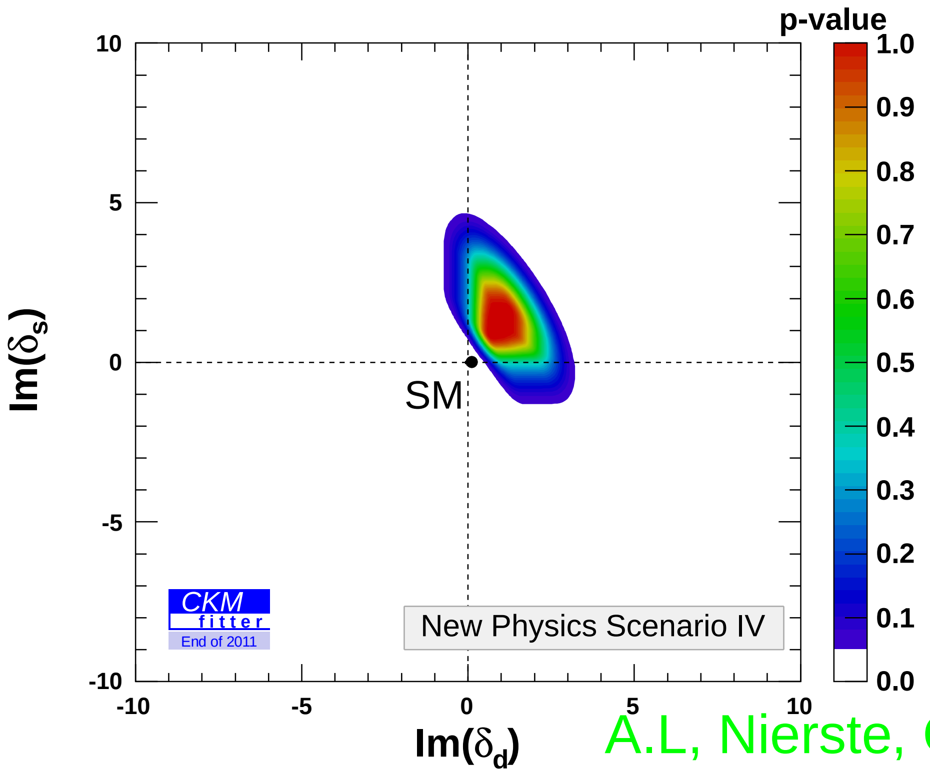
  Buchalla, Dunietz, Yamamoto '95

  - $n_c^{\text{Exp.}} < n_c^{\text{Theory}}$ = missing charm puzzle
    May be enhanced $b \to s\ g$... Kagan ...
  - latest Data from BaBar and CLEO agree within large uncertainties
    Recent and future experiments can do better!
  - Any unknown, even invisible decay mode has an effect on $r(0, 1, 2 \text{ charm})$

!!! $\Rightarrow$ Need new experimental values for $r(0c, 1c, 2c) = \Gamma_{0c,1c,2c}/\Gamma_{sl}$ and B_{sl}!!!

?New physics in Γ_{12}?

Step I: Forget about all the bounds and fit $\Delta\Gamma$, a_{sl} and ΔM:



A.L, Nierste, CKMfitter 1203.0238

Step II: Take your favourite model which gives new contributions to Γ_{12}

- Determine contributions to δ_d, δ_s
- Determine contributions to τ_{B_s}, n_c, ...
- *Exclude the model :-)*

How large are Penguins?

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

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

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! A.L. 1106.3200

Wish-list for Experiments

a) **Congratulations to LHCb for the first measurement of $\Delta\Gamma_s$!**
- Still more precision needed: LHCb, TeVatron, Super-B $B_s \to J/\psi \eta^{(\prime)}$
- Do not use $Br(B_s \to D_s^{(*)+} D_s^{(*)-}) = \frac{\Delta\Gamma^{\rm CP}}{2\Gamma}$ - check size of 3-body FS!

b) $\tau_{B_s} = (1.001 \pm 0.014) \tau_{B_d}$: strong constraint on NP and duality violation
- Combine with other determinations of τ_{B_s}: LHCb, ATLAS?, CMS?
- B_s: Effective lifetimes, flavor specific lifetimes (2.x sigma deviation)
- $\tau_{\Lambda_b}, ...$

c) Di muon asymmetry A_{sl}^b
- HQE fails? **No! At most** $30-40\%$ — more precise test via $\tau(B_s), \Delta\Gamma_s, ...$
- NP acts in Γ_{12}? **No! At most** 40%**!** — More precise tests via $\tau(B_s), \Delta\Gamma_s, \Delta\Gamma_d, n_c, B_{sl}, r(0,1,2 \;\; \text{charm}), B_s \to \tau\tau, B \to K\tau\tau, ...$
- ???
- **Experimental cross-check via a_{sl}^d and a_{sl}^s!**

d) $\phi_s^{LHCb} \ll \phi_s^{A_{sl}^b}$ How large is the penguin pollution?
- Even small penguins can be important!
- **Values** for many penguin modes e.g. $B_s \to J/\psi K_s, K^0 \bar{K}^0, \phi\phi, \eta^{(\prime)}\eta^{(\prime)} ...$

What to do list - Theory

Test of HQE with lifetimes

- τ_{B_s}/τ_{B_d}: Theory is perfect :-)
- τ_{B+}/τ_{B_d}: matrix elements of 4-quark operators - only old lattice values available
- $\tau_{\Lambda_b}/\tau_{B_d}$: matrix elements of 4-quark operators - no real lattice evaluation available
- Precise non-perturbative matrix elements for 4-quark operators urgently needed

Theoretical predictions for mixing observables

- Precise decay constants and Bag parameter for ΔM
- Additional Bag parameters at dimension 6 and 7 for $\Gamma_{12}, \Delta\Gamma, a_{sl}$
- α_s/m_b corrections for Γ_{12}
- α_s^2 corrections for Γ_{12}

Theoretical predictions for charm mixing observables

- Push HQE to its limits
- 4-quark operators for lifetimes — 4-, 6-, 8-quark operators for mixing

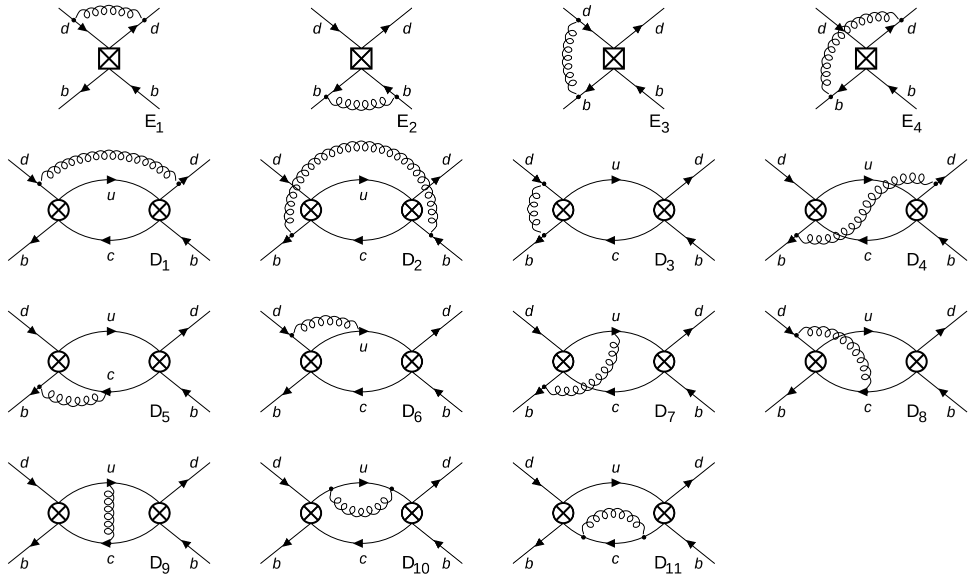
What concrete lattice values to use? How to combine them?

Lifetimes: τ_{B^+}/τ_{B_d} in NLO-QCD I

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

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

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



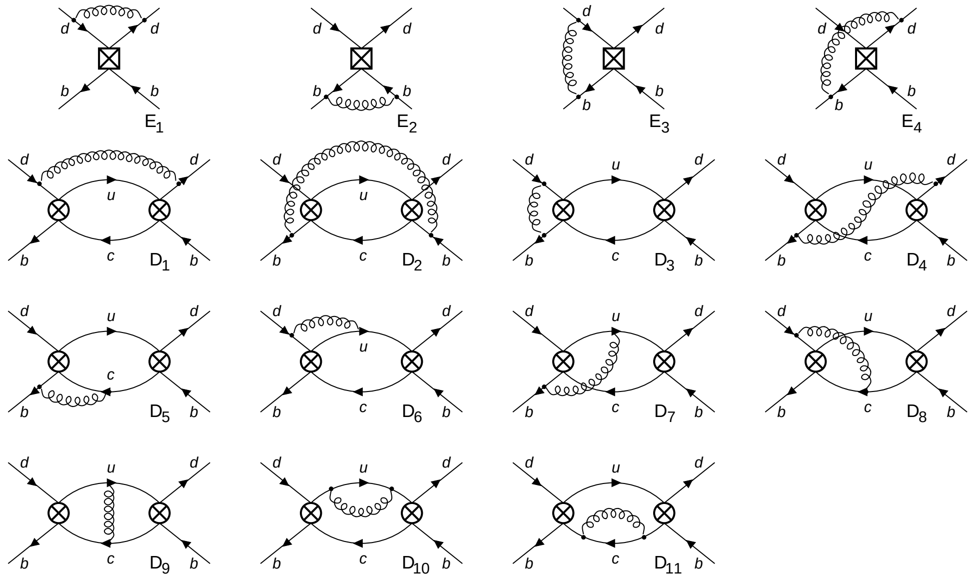
$$\left[\frac{\tau(B^+)}{\tau(B_d^0)}\right]_{\text{LO,NLO,HFAG10}} = 1.047 \pm 0.049 \leftrightarrow 1.063 \pm 0.027 \leftrightarrow 1.071 \pm 0.009$$

Lifetimes: τ_{B^+}/τ_{B_d} in NLO-QCD II

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

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

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



$$\left[\frac{\tau(B^+)}{\tau(B_d^0)}\right]_{\mathrm{LO,NLO,HFAG11}} = 1.047 \pm 0.049 \leftrightarrow 1.044 \pm 0.024 \leftrightarrow 1.079 \pm 0.007$$

Lifetimes: τ_{B^+}/τ_{B_d} in NLO-QCD III

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

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!

Experiment: $\tau_{\Lambda_b}/\tau_{B_d}$

Year	Exp	Decay	$\tau(\Lambda_b)$ [ps]	$\tau(\Lambda_b)/\tau(B_d)$
2011	HFAG	average	1.425 ± 0.032	0.938 ± 0.022
2010	CDF	$J/\psi\Lambda$	1.537 ± 0.047	1.020 ± 0.031
2009	CDF	$\Lambda_c + \pi^-$	1.401 ± 0.058	0.922 ± 0.038
2007	D0	$\Lambda_c \mu \nu X$	1.290 ± 0.150	$0.849 \pm 0.099*$
2007	D0	$J/\psi\Lambda$	1.218 ± 0.137	$0.802 \pm 0.090*$
2006	CDF	$J/\psi\Lambda$	1.593 ± 0.089	1.049 ± 0.059
2004	D0	$J/\psi\Lambda$	1.22 ± 0.22	0.87 ± 0.17
2003	HFAG	average	1.212 ± 0.052	0.798 ± 0.034
1998	OPAL	$\Lambda_c l$	1.29 ± 0.25	$0.85 \pm 0.16*$
1998	ALEPH	$\Lambda_c l$	1.21 ± 0.11	$0.80 \pm 0.07*$
1995	ALEPH	$\Lambda_c l$	1.02 ± 0.24	$0.67 \pm 0.16*$
1992	ALEPH	$\Lambda_c l$	1.12 ± 0.37	$0.74 \pm 0.24*$

LHCb will improve that!!!!

Theory: $\tau_{\Lambda_b}/\tau_{B_d}$

Year	Author	$\tau(\Lambda_b)/\tau(B_d)$
2007	Tarantino	0.88 ± 0.05
2004	Petrov et al.	0.86 ± 0.05
2003	Tarantino	0.88 ± 0.05
2002	Rome	0.90 ± 0.05
2000	Körner,Melic	$0.81 ... 0.92$
1999	Guberina,Melic,Stefanic	0.90
1999	diPierro, Sachrajda, Michael	0.92 ± 0.02
1999	Huang, Liu, Zhu	0.83 ± 0.04
1996	Colangelo, deFazio	> 0.94
1996	Neubert,Sachrajda	” > 0.90”
1992	Bigi, Blok, Shifman, Uraltsev, Vainshtein	$> 0.85 ... 0.90$
x	only$1/m_b^2$	0.98

Theory: $\tau_{\Lambda_b}/\tau_{B_d}$ at order $1/m_b^2$

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} = 1 + \frac{\Lambda^2}{m_b^2}\left(\Gamma_2^{(0)} + \ldots\right) + \frac{\Lambda^3}{m_b^3}\left(\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{(1)} + \ldots\right) + \frac{\Lambda^4}{m_b^4}\left(\Gamma_4^{(0)} + \ldots\right) + \frac{\Lambda^5}{m_b^5}\left(\Gamma_5^{(0)} + \ldots\right) + \ldots$$

Leading Term

$$\begin{aligned}\frac{\Lambda^2}{m_b^2}\Gamma_2 &= \frac{\mu_\pi^2(\Lambda_b) - \mu_\pi^2(B_d)}{2m_b^2} + c_5\frac{\mu_G^2(\Lambda_b) - \mu_G^2(B_d)}{m_b^2} \\ &= \frac{(0.1 \pm 0.1)\text{GeV}^2}{2m_b^2} + 1.2\frac{0 - 0.33\text{GeV}^2}{2m_b^2} \\ &\approx 0.002 - 0.017 = -0.015\end{aligned}$$

Numbers from Bigi, Mannel Uraltsev, 2011

Theory: $\tau_{\Lambda_b}/\tau_{B_d}$ at order $1/m_b^3$

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} = 1 \quad - \quad 0.015$$
$$+ \quad \frac{\Lambda^3}{m_b^3}\left(\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{(1)} + \ldots\right)$$
$$+ \quad \frac{\Lambda^4}{m_b^4}\left(\Gamma_4^{(0)} + \ldots\right) + \frac{\Lambda^5}{m_b^5}\left(\Gamma_5^{(0)} + \ldots\right) + \ldots$$

Γ_3 is a linear combination of perturbative Wilson coefficients and non-perturbative matrix elements

- Wilson coefficient of $\Gamma_3^{(0)}$, e.g. 1996 Neubert and Sachrajda
  Part of $\Gamma_3^{(1)}$ 2002 Franco, Lubicz, Mescia, Tarantino
- Matrixelement
  HQET: only two different matrix elements (instead of four)

$$\frac{1}{2m_{\Lambda_b}}\langle\Lambda_b|\bar{b}_L\gamma_\mu q_L \cdot \bar{q}_L\gamma^\mu b_L|\Lambda_b\rangle =: -\frac{f_B^2 m_B}{48} r$$

$\tau_{\Lambda_b}/\tau_{B_d}$: matrix elements of 4-quark operators

Values for r:

$r \approx 0.2$ *Bag model* Guberina, Nussino, Peccei, Rückl, 1979

$r \approx 0.5$ *NR quark model* –"–

$r = 0.9 \pm 0.1$ *spectroscopy* Rosner, 1996

$r = 1.8 \pm 0.5$ *spectroscopy* –"–

$r = 0.2 \pm 0.1$ *QCD sum rules* Colangelo, de Fazio, 1996

Neubert, Sachrajda: $\frac{\tau(\Lambda_b)}{\tau(B_d^0)}$ " > 0.9"

$r = 1.2 \pm 0.2 \pm ?$ *lattice* di Pierro, Sachrajda, Michael 1999

$r = 2.3 \pm 0.6$ *QCD sum rules* Huang, Liu, Zhu, 2000

$r = 6.2 \pm 1.6$ *QCD sum rules* –"–

$$!!! \quad \frac{\tau(\Lambda_b)}{\tau(B_d^0)} - 1 \propto r \quad !!!$$

$\tau_{\Lambda_b}/\tau_{B_d}$: matrix elements of 4-quark operators

1996 Rosner

$$r = \frac{4}{3} \frac{m^2_{\Sigma_b^*} - m^2_{\Sigma_b}}{m^2_{B^*} - m^2_B}$$

In 1996 b-baryon masses were hardly known

- $m^2_{\Sigma_b^*} - m^2_{\Sigma_b} \approx m^2_{\Sigma_c^*} - m^2_{\Sigma_c} = (0.384 \pm 0.035)$GeV^2

$$\Rightarrow r = 0.9 \pm 0.10$$

- $m_{\Sigma_b^*} - m_{\Sigma_b} = (56 \pm 16)$ MeV

$$\Rightarrow r = 1.8 \pm 0.5$$

- Use the values from PDG 2011

$$\Rightarrow r = 0.68 \pm 0.10$$

$\tau_{\Lambda_b}/\tau_{B_d}$: matrix elements of 4-quark operators

1999 DiPierro, Sachrajda, Michael:
currently the only lattice determination

- 13 years old
- The authors call their study *exploratory*
  - Larger lattice should be used
  - Larger sample of gluon configurations should be used
  - Matching to continuum only at leading order
  - No chiral extrapolation attempted
  - Penguin contractions are missing

1999 Huang, Liu, Zhu:
QCD sum rule result, which is up to a factor of 31 larger than the one by Colangelo and DeFazio

Matrix elements for Γ_{12}

- In the calculation of $1/m_b^3$ corrections to Γ_{12} 4 operators arise:
  - $Q, Q_S, \tilde{Q}, \tilde{Q}_S$ – *tilde* means *color rearranged*
  - They are not independent: ($\alpha_i = 1 + \mathcal{O}(\alpha_s)$)

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

- In the calculation of $1/m_b^4$ corrections to Γ_{12} 6 operators arise:

$$\begin{aligned} R_1 &= \frac{m_s}{m_b} \, \bar{s}_\alpha (1+\gamma_5) b_\alpha \, \bar{s}_\beta (1-\gamma_5) b_\beta \\ R_2 &= \frac{1}{m_b^2} \, \bar{s}_\alpha \overleftarrow{D}_\rho \gamma^\mu (1-\gamma_5) D^\rho b_\alpha \, \bar{s}_\beta \gamma_\mu (1-\gamma_5) b_\beta \\ R_3 &= \frac{1}{m_b^2} \, \bar{s}_\alpha \overleftarrow{D}_\rho (1+\gamma_5) D^\rho b_\alpha \, \bar{s}_\beta (1+\gamma_5) b_\beta \end{aligned}$$

$$\Gamma_{12} = \Gamma_{12}\left(f_{B_s}, B, B_S, B_{R_0}, B_{R_1}, B_{R_2}, B_{R_3}, B_{\tilde{R}_1}, B_{\tilde{R}_2}, B_{\tilde{R}_3}\right)$$

Matrix elements for Γ_{12}

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

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

- $1/m_b$ turned out to be large 1996 Beneke, Buchalla, Dunietz
- Till now only *Vacuum Insertion Approximation* and an estimate of factorizable terms with QCD sum rules 2007 Mannel, Pecjak, Pivovarov available for dimension 7 operators
- Now the dominant error!!!!

$\Delta\Gamma_s$ in NLO-QCD II

Improvement in theoretical accuracy

$\Delta\Gamma_s^{\mathrm{SM}}$	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%

How to combine lattice values?

Suggestions

1. Take only values from close friends working on the lattice
2. Take lattice errors from conservative groups at its face value, multiply the errors of more aggressive groups by a factor of n
3. Be conservative:
   E.g. we had here 3 results for the B_s decay constant
   - $f_{B_s} = 232(10)$ MeV $= 222...242$ Petros Dimopoulos
   - $f_{B_s} = 242(10)$ MeV $= 232...252$ Andreas Kronfeld
   - $f_{B_s} = 225(04)$ MeV $= 221...229$ Christine Davies

$$\Rightarrow f_{B_s} \in [221, 252] = 236.5 \pm 15.5$$

We really need serious conservative suggestions to make strong claims about the validity of the standard model!

What to do with systematic errors that cannot be relieably estimated? Set them to zero?

For all who did not attend the Trento workshop

The suggestions on the previous slide were suppossed to be a joke!!!

Moriond 2012: Conclusion from B-Mixing

It is actually not bad, what the Grinch left for us

Expansion in $1/m_b$ works so well,
What does this tell about charm? $1/m_c \approx 3 \cdot 1/m_b$

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

Many observables in the B_s mixing system:

Elimination of $\Gamma_{12}^{\rm Theo}$ via (No hint for incorrectness of $\Gamma_{12}^{\rm Theo}$ except: A_{sl}^b is 1.5σ above bound)

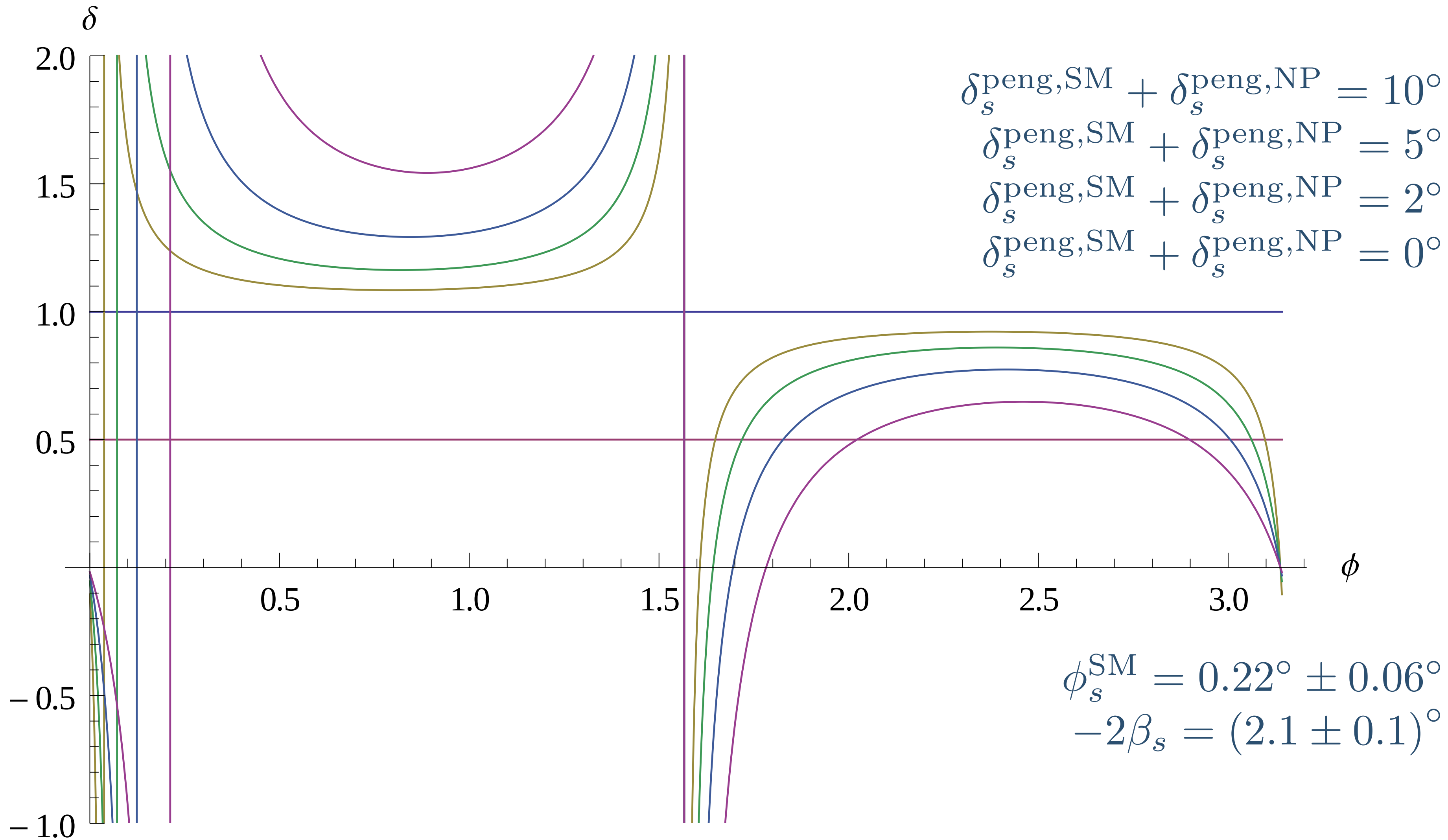
$$a_{sl}^s \quad = \quad -\frac{\Delta\Gamma}{\Delta M}\frac{S_{\psi\phi}}{\sqrt{1-S_{\psi\phi^2}}}\cdot\delta$$

not possible at that simple level, because $\delta \neq 1$

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

A.L. 1106.3200

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



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

A.L. 1106.3200

Lifetimes: Lifetimes of heavy hadrons

- $\tau(B^+)/\tau(B_d)$: HQE seems to fit, but we need urgently more precise hadronic matrix elements
-

$$\frac{\tau(B_s)}{\tau(B_d)} = 0.996...1.000 \quad \leftrightarrow \quad 0.969 \pm 0.017 \text{ HFAG 2011}$$

$$\text{A.L. 1102.4274} \quad \leftrightarrow \quad 1.004 \pm 0.018 \text{ LHCb-Conf2011-049}$$

More data as well as non-perturbative matrix elements needed

- $\tau(\Lambda_b)$, $\tau(\Xi_b)$ and $\tau(B_c)$: more data and further theory work (perturbative and non-perturbative) neccessary

- $\tau(D)$, D-mixing: work in progress
  Bigi, Uraltsev 2001; Bobrowski, A.L., Riedl, Rohrwild 1002.4794; 1011.5608; Bobrowski, A.L. Nierste, Prill, to appear
  It is not unplausible that HQE might give reasonable estimates

Theory statements about CPV in D before LHCb

[1002.4794] How large can the SM contribution to CP violation in $D^0-\bar D^0$ mixing be? - Mozilla Firefox

arxiv.org/abs/arXiv:1002.4794

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High Energy Physics - Phenomenology

How large can the SM contribution to CP violation in $D^0-\bar D^0$ mixing be?

M. Bobrowski, A. Lenz, J. Riedl, J. Rohrwild

(Submitted on 25 Feb 2010)

We investigate the maximum size of CP violating effects in D-mixing within the Standard Model (SM), using Heavy Quark Expansion (HQE) as theoretical working tool. For this purpose we determine the leading HQE contributions and also α_s corrections as well as subleading $1/m_c$ corrections to the absorptive part of the mixing amplitude of neutral D mesons. It turns out that these contributions to Γ_{12} do not vanish in the exact SU$(3)_\mathrm{F}$ limit. Moreover, while the leading HQE terms give a result for Γ_{12} orders of magnitude lower than the current experimental value, we do find a sizeable phase. In the literature it was suggested that higher order terms in the HQE might be much less affected by the severe GIM cancellations of the leading terms; it is even not excluded that these higher order terms can reproduce the experimental value of y. If such an enhancement is realized in nature, the phase discovered in the leading HQE terms can have a sizeable effect. Therefore, we think that statements like: {\it "CP violating effects in D-mixing of the order of 10^{-3} to 10^{-2} are an unambigous sign of new physics"}--given our limited knowlegde of the SM prediction--are premature. Finally, we give an example of a new physics model that can enhance the leading HQE terms to Γ_{12} by one to two orders of magnitude.

Comments: 14 pages, considerably extended version of 0904.3971 with completely new main aspect; text (except title and abstract) identical to the version accepted by JHEP

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Experiment (hep-ex)

Journal reference: JHEP 03(2010)009

Report number: DO-TH 10/04,TTK-10-2

Cite as: **arXiv:1002.4794v1 [hep-ph]**

Submission history

From: Alexander Lenz [view email]

[v1] Thu, 25 Feb 2010 14:27:00 GMT (97kb)

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