Lifetimes and mixing parameters of neutral b hadrons

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Karlsruhe Institute of Technology

CKM2010, September 2010

in memory of Nicola Cabibbo
(10 Apr 1935 – 16 Aug 2010)

May 14, 2010

Fermilab Wine&Cheese seminar, talk by Guennadi Borrisov:

Evidence for an anomalous like-sign dimuon charge asymmetry

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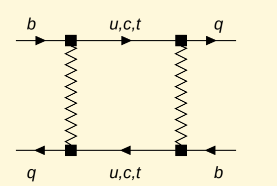
> *Joe Lykken, a theorist at Fermilab, said, "So I would not say that this announcement is the equivalent of seeing the face of God, but it might turn out to be the toe of God."*

Contents

$\mathrm{B}-\overline{\mathrm{B}}$ mixing basics

Consider $\mathrm{B_q}-\overline{\mathrm{B}}_\mathrm{q}$ mixing with $q = d$ or $q = s$:

A meson identified ("tagged") as a B_q at time $t = 0$ is described by $|B_q(t)\rangle$.



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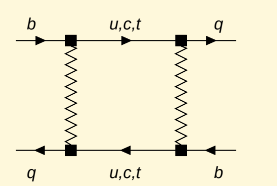

For $t > 0$:

$$|B_q(t)\rangle = \langle B_q|B_q(t)\rangle\,|B_q\rangle \;+\; \langle \overline{B}_q|B_q(t)\rangle\,|\overline{B}_q\rangle + \ldots,$$

with "$\ldots$" denoting the states into which $B_q(t)$ can decay.

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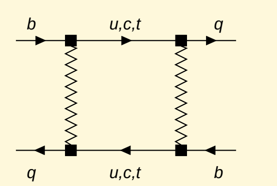

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Analogously: $|\overline{B}_q(t)\rangle$ is the ket of a meson tagged as a $\overline{B}_q$ at time $t = 0$.

Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix}\langle B_q|B_q(t)\rangle\\ \langle \bar{B}_q|B_q(t)\rangle\end{pmatrix} = \left(M^q - i\,\frac{\Gamma^q}{2}\right)\begin{pmatrix}\langle B_q|B_q(t)\rangle\\ \langle \bar{B}_q|B_q(t)\rangle\end{pmatrix}$$

with the 2×2 mass and decay matrices $M^q = M^{q\dagger}$ and $\Gamma^q = \Gamma^{q\dagger}$.

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3 physical quantities in $\mathrm{B_q}-\overline{\mathrm{B}}_\mathrm{q}$ mixing:

$$|M_{12}^q|, \quad |\Gamma_{12}^q|, \quad \phi_q \equiv \arg\left(-\frac{M_{12}^q}{\Gamma_{12}^q}\right)$$

Diagonalise $M^q - i\,\frac{\Gamma^q}{2}$ to find the two mass eigenstates:

$$
\begin{aligned}
\text{Lighter eigenstate:} \quad |B_L^q\rangle &= p|B_q\rangle + q|\overline{B}_q\rangle. \\
\text{Heavier eigenstate:} \quad |B_H^q\rangle &= p|B_q\rangle - q|\overline{B}_q\rangle
\end{aligned}
$$

with masses $M_{L,H}^q$ and widths $\Gamma_{L,H}^q$.

Further $|p|^2 + |q|^2 = 1$.

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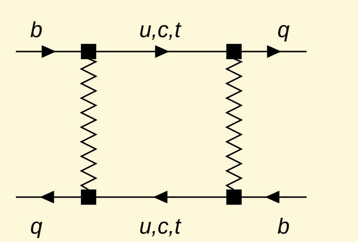
Relation of Δm_q and $\Delta\Gamma_q$ to $|M_{12}^q|$, $|\Gamma_{12}^q|$ and ϕ_q:

$$\begin{aligned} \Delta m_q &= M_H^q - M_L^q \simeq 2|M_{12}^q|, \\ \Delta\Gamma_q &= \Gamma_L^q - \Gamma_H^q \simeq 2|\Gamma_{12}^q|\cos\phi_q \end{aligned}$$

In the Standard Model $\phi_d \approx -5^\circ$ and $\phi_d \approx 0.2^\circ$, so that

$$\Delta\Gamma_q^{\rm SM} \simeq 2|\Gamma_{12}^q|$$

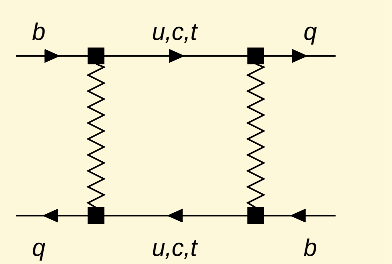
M_{12}^q stems from the dispersive (real) part of the box diagram, internal t.
Γ_{12}^q stems from the absorpive (imaginary) part of the box diagram, internal c, u.



$B-\overline{B}$ mixing and new physics

New physics cannot affect Γ_{12}^s, which stems from CKM-favoured tree-level decays.

New physics can barely affect Γ_{12}^d, which stems from singly Cabibbo-suppressed tree-level decays.



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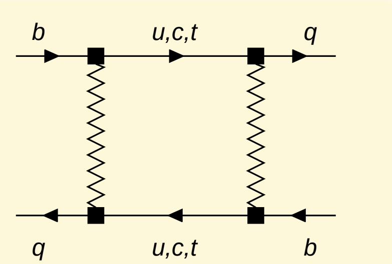

M_{12}^{q} is very sensitive to virtual effects of new heavy particles. A priori new physics at the TeV scale typically comes with $|M_{12}^{q}| \gg |M_{12}^{\mathrm{SM},q}|$ ("new-physics flavour problem").

$\Rightarrow$ Substantial changes in $|M_{12}^{q}|$ and ϕ_q are possible.

Average width: $\Gamma_q = \frac{\Gamma_L^q + \Gamma_H^q}{2}$

SM predictions:

In the ratio $|\Gamma_{12}^q|/|M_{12}^{\mathrm{SM,q}}|$ hadronic uncertainties cancel to a large extent.

$$\frac{|\Gamma_{12}^d|}{|M_{12}^{d,\mathrm{SM}}|} = \frac{2|\Gamma_{12}^d|}{|\Delta m_d^{\mathrm{SM}}|} = \left(53^{+11}_{-13}\right) \cdot 10^{-4}$$

$$\Delta m_d^{\mathrm{exp}} = 0.51\,\mathrm{ps}^{-1} \quad \Rightarrow \quad \left.\frac{2|\Gamma_{12}^d|}{\Gamma_d}\right|_{\mathrm{SM}} = \left(41^{+9}_{-10}\right) \cdot 10^{-4}$$

Lenz, UN 2006

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$$\Delta\Gamma_d = 2|\Gamma_{12}^d| \cos(\phi_d) \geq 2|\Gamma_{12}^d| 0.94$$

because we know from global fits to the unitarity triangle that $-20^\circ \leq \phi_d \leq 3^\circ$ at 3σ CL.

In the B_s system $\Delta\Gamma_s$ is found together with ϕ_s from an angular analysis of $B_s \to J/\psi\phi$ data. The calculated value of $|\Gamma_{12}^s|$ defines the physical “yellow band” in the $(\Delta\Gamma_s, \phi_s)$ plane.

$$2|\Gamma_{12}^s| = (0.096 \pm 0.022) \left[\frac{f_{B_s}\sqrt{B}}{221\text{ MeV}}\right]^2 \text{ps}^{-1}$$

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Update to the 2010 lattice world average
$f_{B_s}\sqrt{B} = 209 \pm 18$ MeV:

$$2|\Gamma_{12}^s| = \Delta\Gamma_s^{\text{SM}} = (0.086 \pm 0.025)\,\text{ps}^{-1}$$

$$\Rightarrow \qquad \frac{\Delta\Gamma_s^{\text{SM}}}{\Gamma_s} = 0.13 \pm 0.04$$

Width difference among the CP eigenstates

$|B_{s,\mathrm{CP}\pm}\rangle = \dfrac{|B_s\rangle \mp |\bar{B}_s\rangle}{\sqrt{2}}$:

$$\Delta\Gamma_{\mathrm{CP}} = 2|\Gamma_{12}|$$

unaffected by new physics!

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In the simultaneous limits of $N_c = \infty$, $m_c \to \infty$ and $m_b - 2m_c \to 0$ one can show

$$2\,Br(\overset{(-)}{B_s} \to D_s^{(*)+} D_s^{(*)-}) = \frac{\Delta\Gamma_{\mathrm{CP}}}{\Gamma_s}\left[1 + \mathcal{O}\left(\frac{\Delta\Gamma}{\Gamma_s}\right)\right]$$

Aleksan et al. 1993

Corrections of order 100% cannot be ruled out.

BELLE (arXiv:1005.5177) finds from $Br(\overset{(-)}{B}_s \to D_s^{(*)+} D_s^{(*)-})$

$$\frac{\Delta\Gamma_{\mathrm{CP}}}{\Gamma_s} = 0.147^{+0.036}_{-0.030}\Big|_{\mathrm{stat}}{}^{+0.044}_{-0.042}\Big|_{\mathrm{syst}}$$

central value right on top of Lenz, UN 2006 prediction.

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- ...the CP-odd eigenstate does not contribute to $\overset{(-)}{B}_s \to D_s^{(*)+} D_s^{(*)-}$. The lifetime measured in any of the contributing modes must therefore be $1/\Gamma_L^s$!

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- ... the CP-odd eigenstate does not contribute to $\overset{(-)}{B}_s \to D_s^{(*)+} D_s^{(*)-}$. The lifetime measured in any of the contributing modes must therefore be $1/\Gamma_L^s$!
- ... no multi-body $c\bar{c}s\bar{s}$ final states occur.

The average B_s width

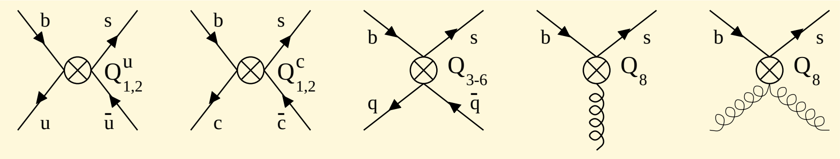
Define

$$\tau_{B_s} \equiv \frac{1}{\Gamma_{B_s}}.$$

Discuss

$$\frac{\tau_{B_s}}{\tau_{B_d}}.$$

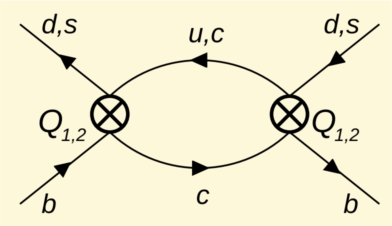
Operators:



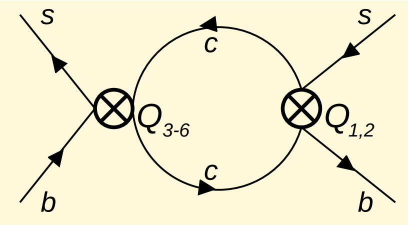
Wilson Coefficients $|C_{1,2}| \gg |C_{3,\ldots 8}|$.

Weak annihilation

contributes to τ_{B_d}, τ_{B_s}:

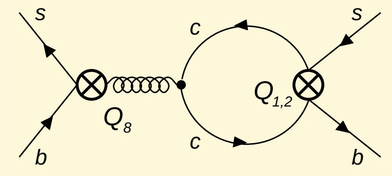


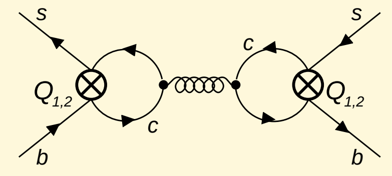
contributes only to τ_{B_s}:



The left diagram gives practically the same result for B_s and B_d.
The right diagram comes with small penguin coefficients $C_{3...6}$.

More small diagrams contributing to τ_{B_s}:





The prediction of τ_{B_s}/τ_{B_d} involves four hadronic matrix element parametrised by $f_B^2 B_1$, $f_B^2 B_2$, $f_B^2 \epsilon_1$ and $f_B^2 \epsilon_2$.

Neubert,Sachrajda 1996

1997 prediction including penguin effects:

$$\frac{\tau(B_s)}{\tau(B_d)} - 1 = (-1.2 \pm 10.0) \cdot 10^{-3} \cdot \left(\frac{f_{B_s}}{190\,\mathrm{MeV}} \right)^2$$

Keum,UN 1997

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With 2001 quenched lattice values (hep-ph/0110124) for the bag parameters and $f_{B_s} = 228 \pm 20\,\mathrm{MeV}$, $f_{B_s}/f_{B_d} = 1.199 \pm 0.031$ find

$$-5 \cdot 10^{-3} \leq \frac{\tau_{B_s}}{\tau_{B_d}} - 1 \leq 10^{-3}$$

HFAG 2010: $\frac{\tau_{B_s}}{\tau_{B_d}} - 1 = -0.035 \pm 0.017$.

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This is 1.8σ away from $-5 \cdot 10^{-3}$.
The discrepancy can be slightly alleviated with a positive new physics contribution to C_4.

Global analysis of $B_s-\overline{B}_s$ mixing and $B_d-\overline{B}_d$ mixing

Based on work with A. Lenz and the CKMfitter Group
(J. Charles, S. Descotes-Genon, A. Jantsch, C. Kaufhold,
H. Lacker, S. Monteil, V. Niess) arXiv:1008.1593

Rfit method: No statistical meaning is assigned to systematic errors and theoretical uncertainties.

We have performed a simultaneous fit to the Wolfenstein parameters and to the new physics parameters Δ_s and Δ_d:

$$\Delta_q \equiv \frac{M_{12}^q}{M_{12}^{q,\mathrm{SM}}}, \qquad \Delta_q \equiv |\Delta_q| e^{i\phi_q^\Delta}.$$

CP asymmetries in flavour-specific decays (semileptonic CP asymmetries):

$$a_{\rm fs}^d = \frac{|\Gamma_{12}^d|}{|M_{12}^d|} \sin\phi_d = \frac{|\Gamma_{12}^d|}{|M_{12}^{\rm SM,d}|} \cdot \frac{\sin\phi_d}{|\Delta_d|} = \left(5.26^{+1.15}_{-1.28}\right) \cdot 10^{-3} \cdot \frac{\sin\phi_d}{|\Delta_d|}$$

$$a_{\rm fs}^s = \frac{|\Gamma_{12}^s|}{|M_{12}^s|} \sin\phi_s = \frac{|\Gamma_{12}^s|}{|M_{12}^{\rm SM,s}|} \cdot \frac{\sin\phi_s}{|\Delta_s|} = (4.97 \pm 0.94) \cdot 10^{-3} \cdot \frac{\sin\phi_s}{|\Delta_s|}$$

A. Lenz, UN, 2006

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Two connections:
(i) The DØ dimuon asymmetry result

$$a_{\mathrm{fs}} = (-9.57 \pm 2.51 \pm 1.46) \cdot 10^{-3}$$

involves a mixture of B_d and B_s mesons with

$$a_{\mathrm{fs}} = (0.506 \pm 0.043) a_{\mathrm{fs}}^d + (0.494 \pm 0.043) a_{\mathrm{fs}}^s$$

(ii) The global fit to the unitarity triangle involves $\Delta m_d / \Delta m_s$ as an important constraint.

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Note: in the presence of new physics $A_{CP}^{\mathrm{mix}}(B_d \to J/\psi K_{\mathrm{short}})$ measures $\sin(2\beta + \phi_d^\Delta)$ rather than $\sin(2\beta)$.

Three scenarios:

Scenario I: arbitrary complex parameters Δ_s and Δ_d

Scenario II: new physics is minimally flavour violating (MFV) (meaning that all flavour violation stems from the Yukawa sector) and y_b is small:
one real parameter $\Delta = \Delta_s = \Delta_d$

Scenario III: MFV with a large y_b: one complex parameter $\Delta = \Delta_s = \Delta_d$

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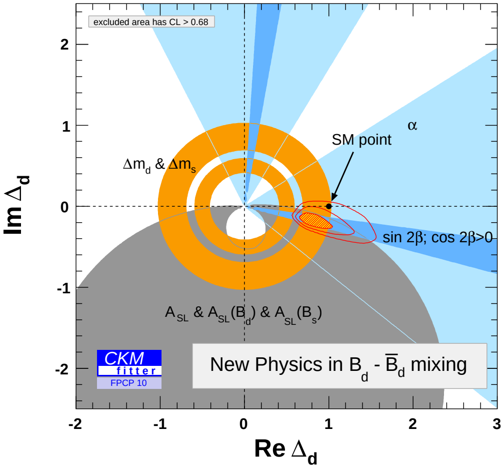
Examples: Scenario I covers the MSSM with generic flavour structure of the soft terms and small $\tan\beta$.
Scenario II covers the MSSM with MFV and small $\tan\beta$.
Scenario III covers certain two-Higgs models (but not the MFV-MSSM).

Results in scenario I:



SM point $\Delta_d = 1$ disfavoured by $\geq 2.5\sigma$.

$\phi_d^\Delta < 0$ helps to explain DØ dimuon asymmetry.

Reason for the tension with the SM: $B(B^+ \to \tau^+ \nu_\tau)$

SM prediction (CL$=2\sigma$):

$$B(B^+ \to \tau^+ \nu_\tau) = \left(0.763^{+0.214}_{-0.097}\right) \cdot 10^{-4}$$

Average of several measurements by BaBar and Belle:

$$B^{\mathrm{exp}}(B^+ \to \tau^+ \nu_\tau) = (1.68 \pm 0.31) \cdot 10^{-4}$$

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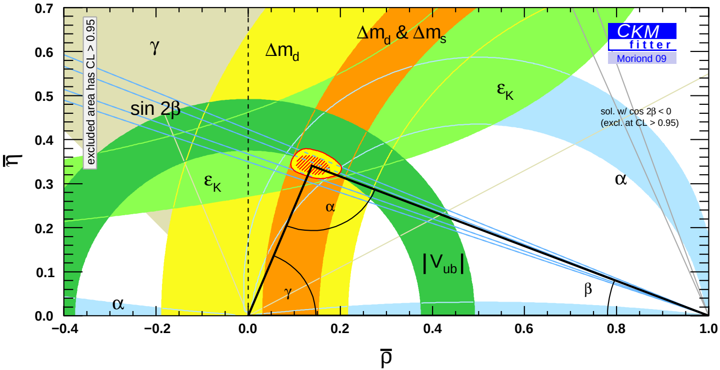
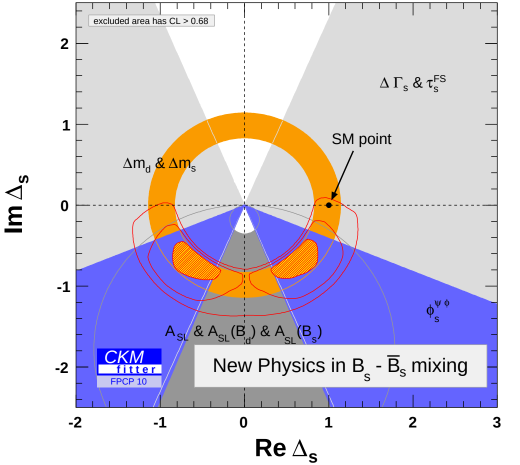
$$B^{\rm SM}(B^+ \to \tau^+\nu_\tau) = \frac{G_F^2 m_{B^+} m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_{B^+}^2}\right)^2 |V_{ub}|^2 f_B^2 \tau_{B^+}.$$

But with e.g. $f_B = 210\,\mathrm{MeV}$ and $|V_{ub}| = 4.4 \cdot 10^{-3}$ find $B^{\rm SM}(B^+ \to \tau^+\nu_\tau) = 1.51 \cdot 10^{-4}$. These parameters comply with the global fit to the UT only, if new physics changes the constraints from $A_{CP}^{\rm mix}(B_d \to J/\psi K_{\rm short})$, Δm_d or $\Delta m_d/\Delta m_s$.

Global fit in the SM:





SM point $\Delta_s = 1$ dis-favoured by $\geq 2.7\sigma$.

without 2010 CDF/DØ data on $B_s \to J/\psi\phi$

Global fit to UT hinting at $\phi_d^\Delta < 0$:
Other authors have seen a tension with the SM in the same direction stemming from ϵ_K.

Lunghi,Soni; Buras,Guadagnoli

In our fit the tension with ϵ_K is mild, because we use a more conservative error on the hadronic parameter $\widehat{B}_K = 0.724 \pm 0.004 \pm 0.067$ and because the Rfit method is more conservative.

p-values:

Calculate χ^2/N_{dof} with and without a hypothesis to find:

Hypothesis	p-value
$\Delta_d = 1$	$2.5\,\sigma$
$\Delta_s = 1$	$2.7\,\sigma$
$\Delta_d = \Delta_s = 1$	$3.4\,\sigma$
$\Delta_d = \Delta_s$	$2.1\,\sigma$

Fit result at 95%CL:

$$\phi_s^{\Delta} = (-51^{+32}_{-25})^\circ \qquad \text{(and } \phi_s^{\Delta} = (-129^{+28}_{-27})^\circ\text{)}$$

Compare with the 2010 CDF/DØ result from $B_s \to J/\psi\phi$:

CDF: $\phi_s^{\Delta} = (-29^{+44}_{-49})^\circ$ at 95%CL

DØ: $\phi_s^{\Delta} = (-44^{+59}_{-51})^\circ$ at 95%CL

Naive average: $\phi_s^{\text{avg}} = (-36 \pm 35)^\circ$ at 95%CL

Is the result driven by the DØ dimuon asymmetry?
One can remove a_{fs} as an input and instead predict it from the global fit:

$$a_{\mathrm{fs}} = \left(-4.2^{+2.7}_{-2.6}\right) \cdot 10^{-3} \qquad \text{at } 2\sigma.$$

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This is just 1.5σ away from the DØ/CDF average

$$a_{\rm fs} = (-8.5 \pm 2.8) \cdot 10^{-3}.$$

The fit in scenario II (real $\Delta_s = \Delta_d$) is not better than the SM fit and gives $\Delta = 0.907^{+0.091}_{-0.067}$.

Scenario III (complex $\Delta_s = \Delta_d$) fits the data quite well irrespective of whether $B(B^+ \to \tau^+\nu_\tau)$ is included or not.

Hypothesis	p-value
$\Delta = 1$	$3.1\ \sigma$

Conclusions

- Updated predictions:

$$2|\Gamma_{12}^s| = \Delta\Gamma_s^{\mathrm{SM}} = (0.086 \pm 0.025)\,\mathrm{ps}^{-1}$$

and $$-5 \cdot 10^{-3} \leq \frac{\tau_{B_s}}{\tau_{B_d}} - 1 \leq 10^{-3}.$$

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- A global fit to the UT indeed shows a slight preference for a new CP phase $\phi_d^\Delta < 0$, driven by $B(B^+ \to \tau^+\nu_\tau)$ (and possibly ϵ_K). In a simultaneously global fit to the UT and the $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing complex a plausible picture of new CP-violating physics emerges.

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  The Standard Model is already falsified from cosmological data and neutrino experiments. LHCb could be the first terrestrial experiment to see imprints of new TeV-scale physics.

A pinch of new physics in $B-\overline{B}$ mixing?