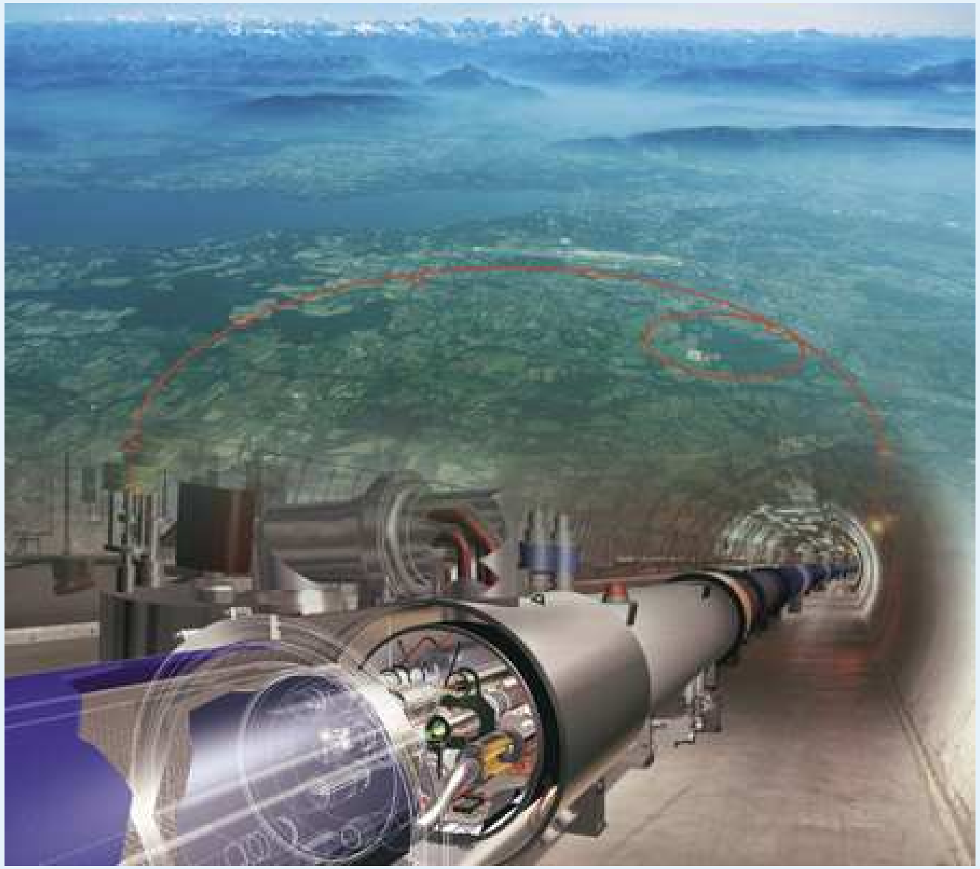
New Physics in B-Mixing



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The simplest Extension of the SM

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New Physics in B_s-Mixing? - Strategy

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

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

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

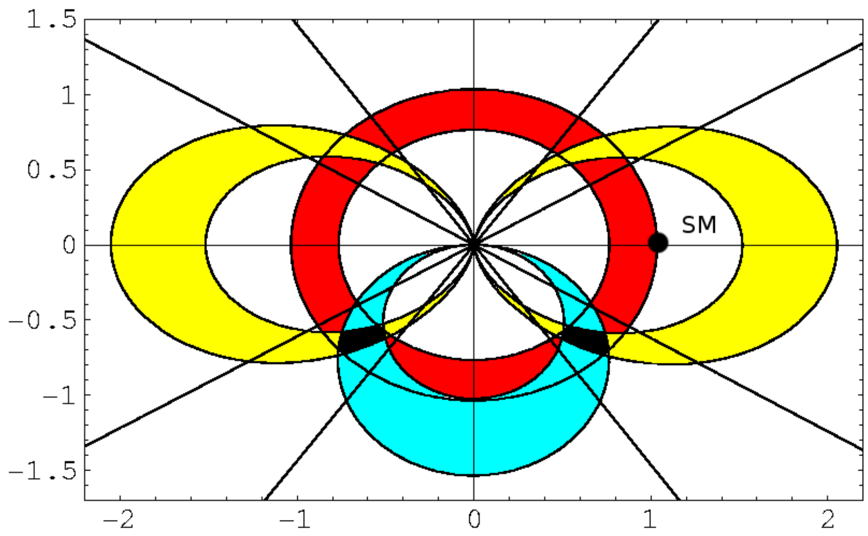
$$\Delta\Gamma_s = 2|\Gamma_{12,s}| \cdot \cos\left(\phi_s^{\text{SM}} + \phi_s^\Delta\right)$$

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

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

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

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



A.L, Nierste, 2006

New Physics in B_s-Mixing? - Dimuon asymmetry

$$A_{sl}^b = 0.494 a_{sl}^s + 0.506 a_{sl}^d \quad = \begin{cases} (-2.3^{+0.5}_{-0.6}) \cdot 10^{-4} & \text{LN 2006} \\ (-2.0 \pm 0.3) \cdot 10^{-4} & \text{LN 2011} \\ (-95.7 \pm 25.1 \pm 14.6) \cdot 10^{-4} & \text{D0,1005.2757} \end{cases}$$

- Statistical significance: 3.2 sigma
- Exp/Theory $\approx$ 42 (Douglas Adams)

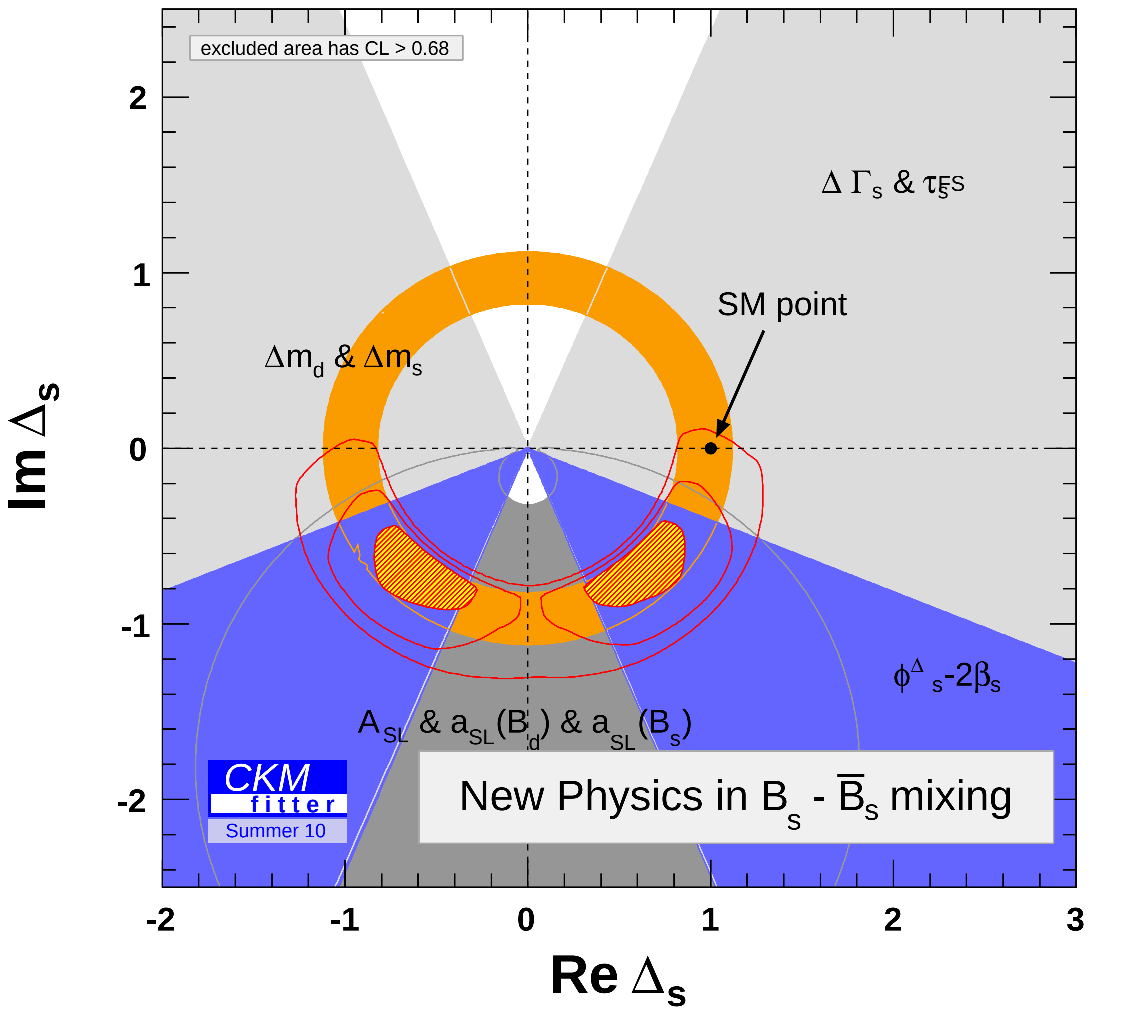
New Physics in B_s-Mixing? - Dimuon asymmetry

- 17.5.2010 **New York Times**
  A new Clue to explain existence
- 19.5.2010 **BBC News**
  New Clue to anti-matter mystery
- 20.5.2010 **Scientific American**
  Fermilab finds new mechanism for matter's dominance over antimatter
- 20.5.2010 **The Times**
  Atom-smasher takes man closer to heart of matter
- 25.5.2010 **Spiegel**
  Neue Asymmetrie zwischen Materie und Antimaterie entdeckt
- 28.5.2010 **Science**
  Hints of greater matter-antimatter asymmetry challenge theorists
- 28.5.2010 **Die Zeit**
  Rätselhafte Asymmetrie
- 29.5.2010 **Chicago Tribune**
  Fermilab test throws off more matter than antimatter - and this matters
- ...

New Physics in B_s-Mixing? - State of the art

CKM Fit with Δ_s and Δ_d (talk of U. Nierste, A. L., U. Nierste, CKMfitter 1008.1593)

- **Im Δ_d = 0 = Im Δ_s is excluded with 3.8 σ**



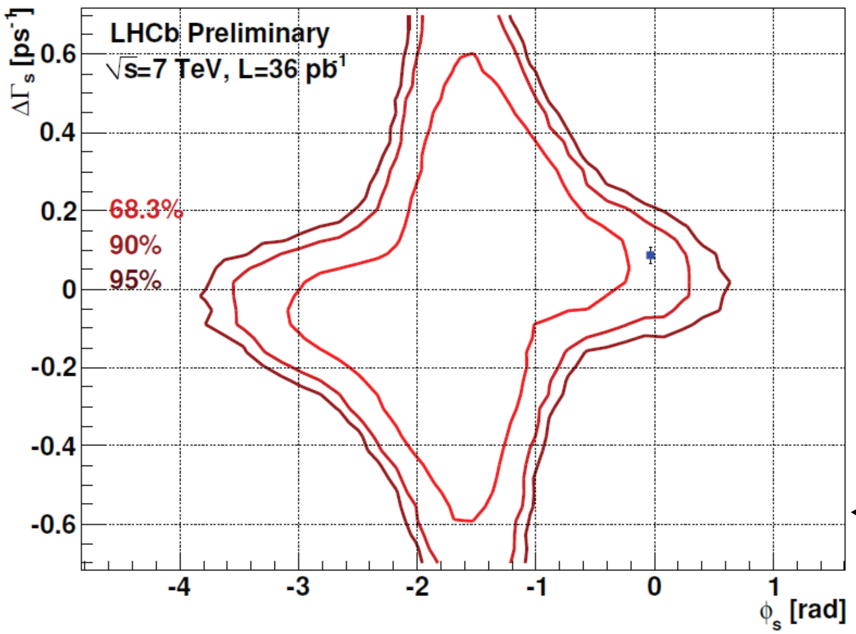
New Physics in B_s-Mixing? - The bright future

Talk from Uli Uwer, april 5th 2011, Beauty 2011, amsterdam

Constraints on phase ϕ_s

new

LHCb-Conf-2011-006



- No meaningful point-estimate ⇒ Confidence contours using Feldman-Cousins method.
- Statistical error only: Accounts for syst. uncertainty of tagging (small).
- Compared to statistical error all systematic effects are negligible

← SM *P*-value: 22% ("1.2σ")

$\phi_s \in [-2.7, -0.5]$ rad at 68% CL
$\phi_s \in [-3.5, 0.2]$ rad at 95% CL

Standard Model:
$\Delta\Gamma_s = 0.087 \pm 0.021$ ps-1
(A.Lenz, U.Nierste, arXiv:1102.4274)
$\phi_s = -0.0363 \pm 0.0017$ rad (CKMfitter)

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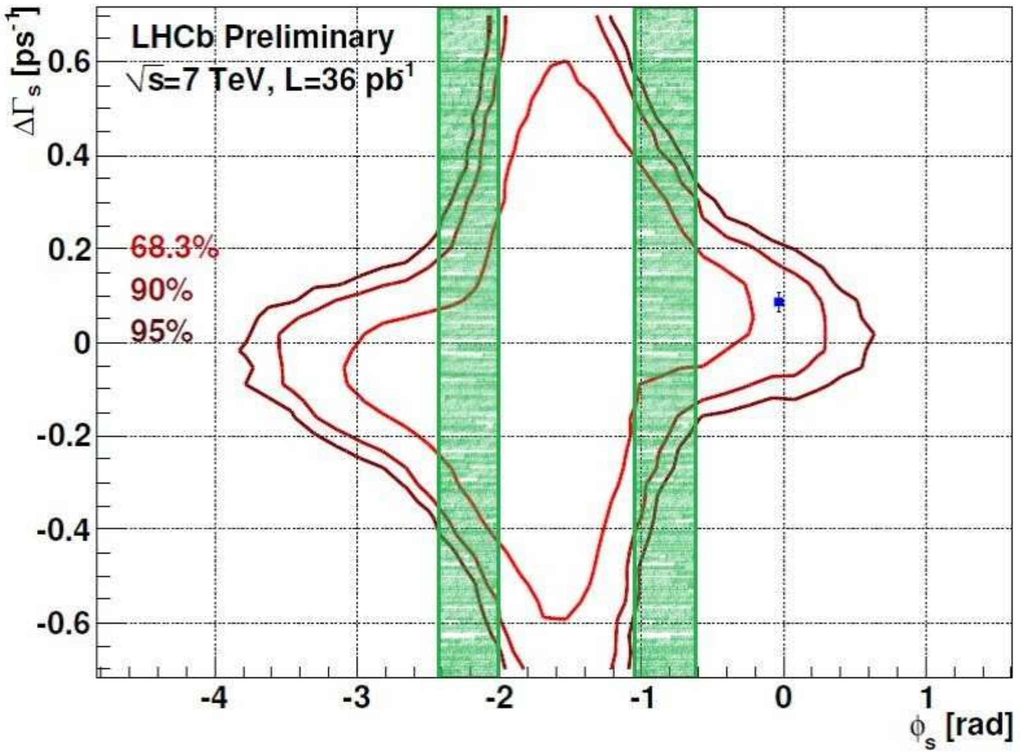
New Physics in B_s-Mixing? - The bright future

Fit result from 1008.1593

This will be an exciting year!!!



The Heavy Quark Expansion

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

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

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

2006: A.L., Nierste

$$\begin{aligned} A_{sl}^{Max.} &\approx \frac{1}{2}\left(5.4 \cdot 10^{-3} \frac{\sin(\phi_d^{SM} + \phi_d^{\Delta})}{|\Delta_d|} + 5.0 \cdot 10^{-3} \frac{\sin(\phi_s^{SM} + \phi_s^{\Delta})}{|\Delta_s|}\right) \\ &\approx \frac{1}{2}\left(5.4 \cdot 10^{-3} \frac{-4.3^\circ - 30^\circ}{0.83} + 5.0 \cdot 10^{-3} \frac{-1}{0.85}\right) \\ &\approx (-4.8 ... -6.1) \cdot 10^{-3} \\ A_{sl}^{D0} &= -9.6 \pm 2.9 \cdot 10^{-3} \end{aligned}$$

The Heavy Quark Expansion

Suggested solutions to this discrepancy

1. Just a statistical fluctuation (1.2 ... 1.7 sigma away from bound)
2. $\mathcal{O}(60\% - 100\%)$ New Physics effects in Γ_{12}
3. $\mathcal{O}(60\% - 100\%)$ Violation of Quark-hadron duality in the HQE

Comments

1) Philosophy in fitting approaches
2) This would also lead to sizeable effects in many other well measuered observables, e.g. $\tau(B_s)/\tau(B_d)$,...
   Grossman, Kagan, A.L., Nierste quantitative analysis in progress
3) Can only be answered exactly, if QCD is solved non-perturbativeley

   Practical approach - such a large effect would be visible

   $\Rightarrow$ **Test OPE II via lifetimes (not sensitive to new physics)**

   $\Rightarrow$ **Calculate corrections in all possible directions ($\alpha_s, 1/m_b$, non-perturbative matrix elements) to test convergence**

   !Problem: Hadronic ME are often only badly known (lattice, sum rules,..)

   $\Rightarrow$ **Apply also to the charm system - the effects are probably larger**

$\Delta\Gamma_s$ in NLO-QCD I

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

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

Numerical update 1102.4274 (A.L., U. Nierste)

if $\phi_s^\Delta \approx 0$: $\Delta\Gamma_s = (0.087 \pm 0.021)$ ps^{-1}

if $\Delta_s \approx 1$: $\frac{\Delta\Gamma_s}{\Gamma_s} = 0.137 \pm 0.027$

Experimental Bounds (HFAG: no external constraints vs. external constraints)

$\Delta\Gamma_s = 0.070 \pm 0.039$ ps^{-1} vs. 0.060 ± 0.021 ps^{-1}

$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.105 \pm 0.060$ vs. 0.089 ± 0.032

$\Delta\Gamma_s$ in NLO-QCD II

Improvement in theoretical accuracy

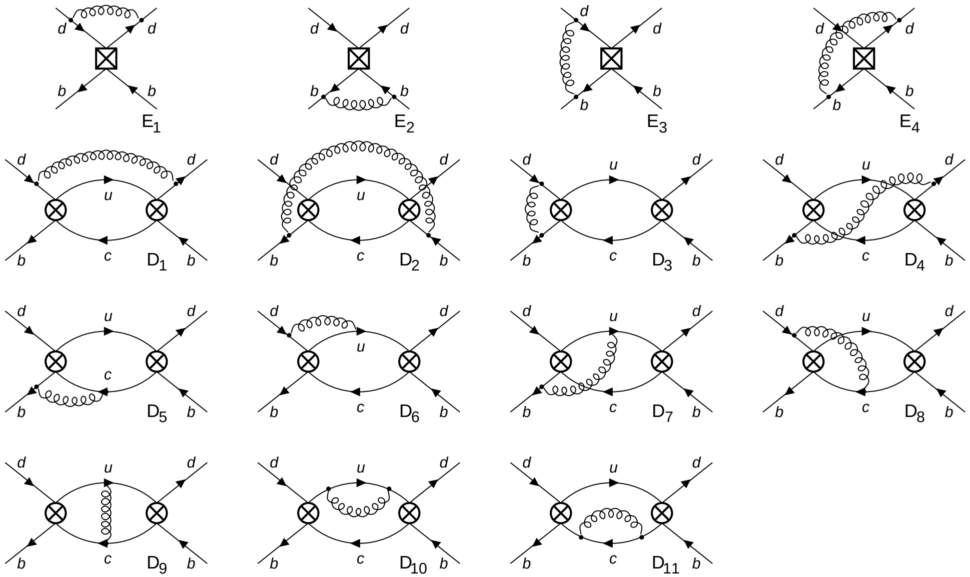
$\Delta\Gamma_s^{\rm SM}$	2011	2006
Central Value	$0.087\,\text{ps}^{-1}$	$0.096\,\text{ps}^{-1}$
$\delta(\mathcal{B}_{\widetilde{R}_2})$	17.2%	15.7%
$\delta(f_{B_s})$	13.2%	33.4%
$\delta(\mu)$	7.8%	13.7%
$\delta(\widetilde{\mathcal{B}}_{S,B_s})$	4.8%	3.1%
$\delta(\mathcal{B}_{R_0})$	3.4%	3.0%
$\delta(V_{cb})$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

τ_{B^+}/τ_{B_d} in NLO-QCD I

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

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

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



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

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

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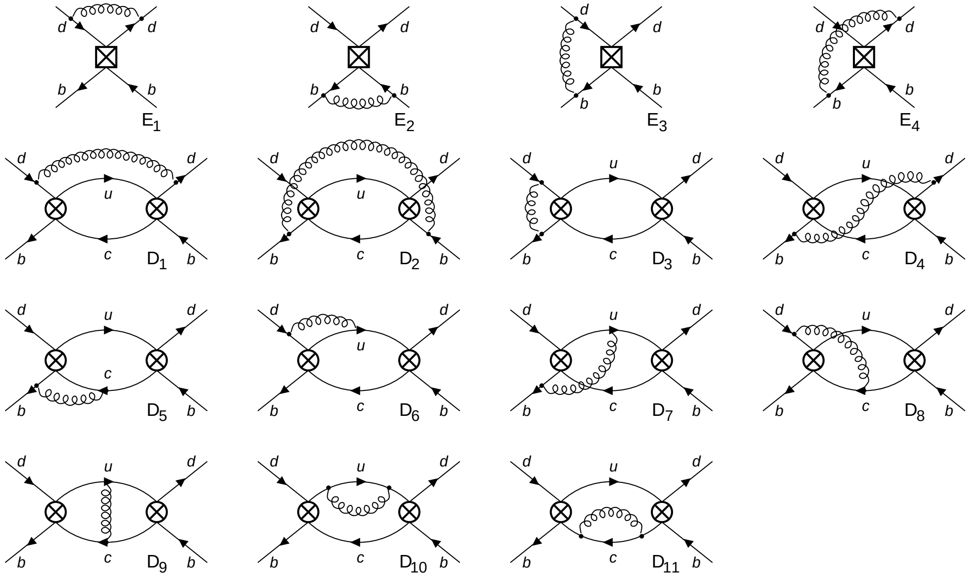


$$\left[\frac{\tau(B^+)}{\tau(B_d^0)}\right]_{\rm LO, NLO, HFAG10} = 1.047 \pm 0.049 \leftrightarrow 1.044 \pm 0.024 \leftrightarrow 1.081 \pm 0.006$$

τ_{B^+}/τ_{B_d} in NLO-QCD III

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

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!

Lifetimes of heavy hadrons

- $\tau(B^+)/\tau(B_d)$: HQE seems to fit, but we need urgently more precise hadronic matrix elements
- $\tau(B_s)/\tau(B_d)$: More data as well as non-perturbative matrix elements needed— $0.996 ... 1.000$ vs. 0.973 ± 0.015
- $\Delta\Gamma_s$: More data needed, theory in relatively good shape (dominant uncertainty: subleading hadronic matrix elements)
- $\tau(\Lambda_b)$, $\tau(\Xi_b)$ and $\tau(B_c)$: more data and further theory work (perturbative and non-perturbative) neccessary
- $\tau(D)$, D-mixing: work in progress
  Bobrowski, A.L., Riedl, Rohrwild 1002.4794; Bobrowski, A.L. 1011.5608; Bobeowski, A.L. Nierste, Prill, to appear
  It is not unplausible that HQE might give reasonable estimates

The SM4

Matter (Spin 1/2, Fermions, 4 Families)

Quarks

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{pmatrix} t' \\ b' \end{pmatrix}$$

Leptons

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \quad \begin{pmatrix} \nu_4 \\ l_4 \end{pmatrix}$$

$\Rightarrow$ New parameters:

- Quark masses: 2
- Lepton masses: 2
- V_{CKM4}: 3 angles + 2 phases
- V_{PMNS4}: 3 angles + 2 phases
  + Majorana-phases

$$V_{CKM4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix}$$

The SM4 became recently quite popular

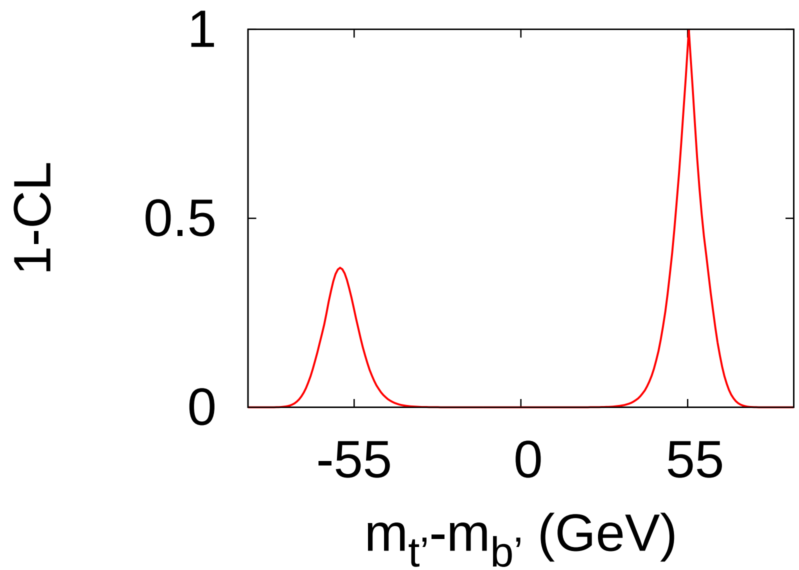
The SM4 - Facts and Fiction I

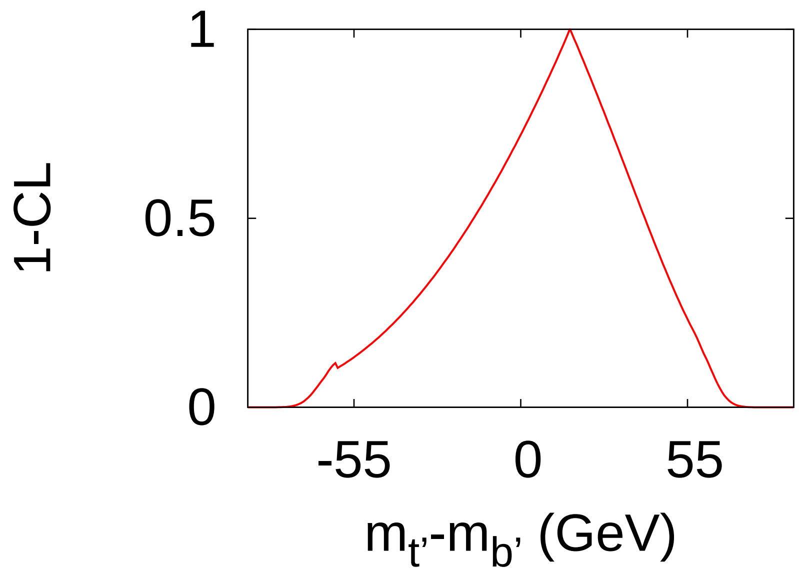
1. **Classical period:** Soni, Hou, et al 1986...
2. **Decline:** LEP: N_ν and S, T, U Langacker und Erler
3. **Resurrection:** Kribs et al 2007; Vysotsky, Okun, et al. 2000-...
   Electroweak observables do not exclude a fourth family!

$$m_{t'} - m_{b'} = \left(1 - \frac{1}{5} \ln \frac{m_H}{115\text{GeV}}\right) \cdot 50\,\text{GeV}$$

4. **Advanced analyses:**
   - Scans over the CKM4 parameter space
     (a) 0902.4883: Bobrowski, A.L., Riedl, Rohrwild - much space
     (b) 0904.3570: Chanowitz - S,T,U reduces space considerably
     (c) 1002.0595: Soni, Alok, Giri, Mohanta - more observables
     (d) 1002.2126: Buras, Duling, Feldmann, Heidsieck, Promberger, Recksiegel
     1004.4565 Charm; 1006.5356 Leptonen
     (e) 1005.3505: Eberhardt, A.L., Rohrwild - full CKM-dependence of S,T,U
   - Complete electro-weak and flavour fit:
     Project with H. Lacker (CKMfitter) and U. Nierste
     see also: 1011.2634: Alok, Dighe, London; talks by Melfo, Melic and Kosnik

The SM4 - Facts and fiction II





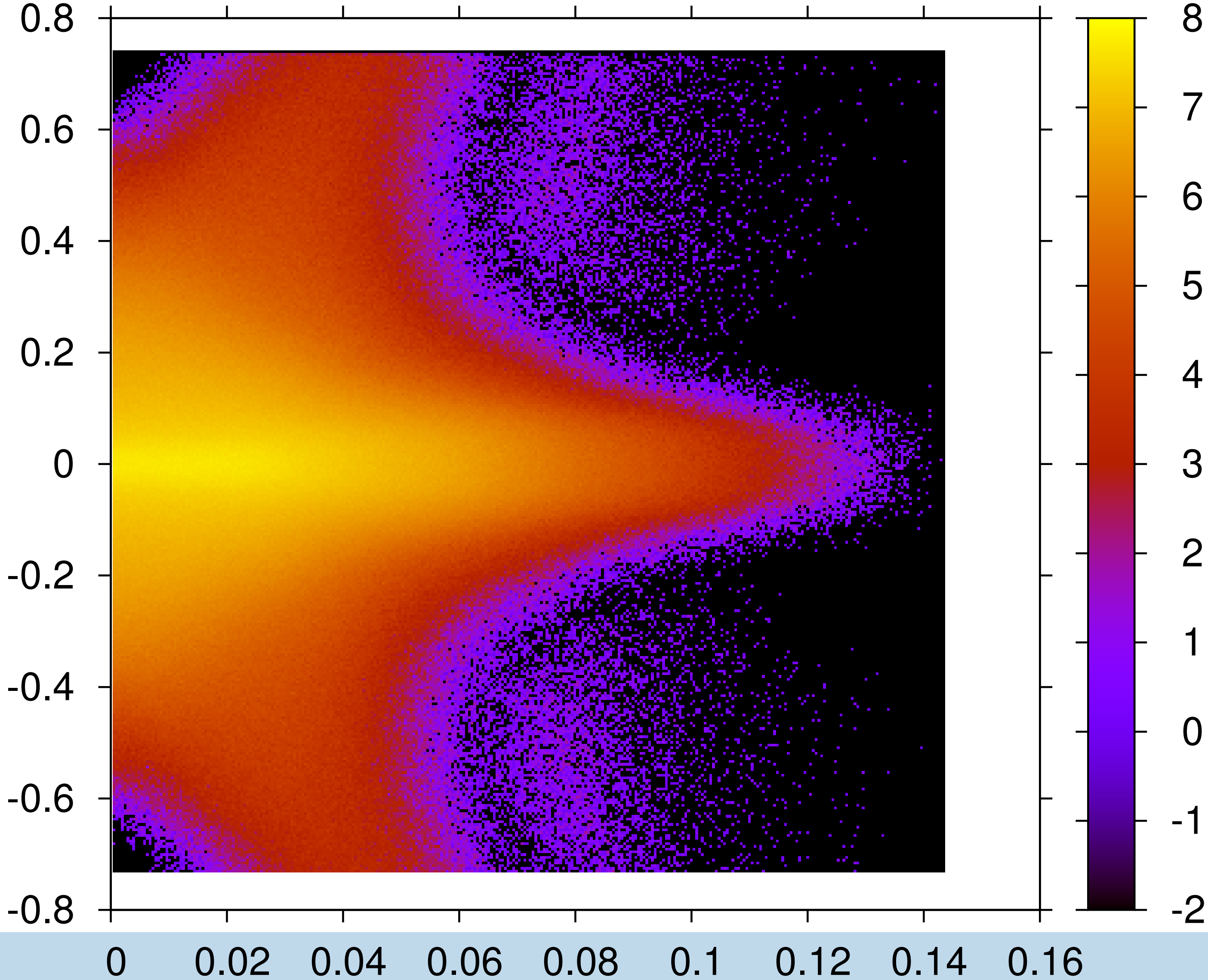
Without CKM Mixing
= Langacker/Erler

With CKM Mixing

In contrast to Langacker/Erler and Chanowitz 2010 and in accordance with GFitter also the lepton masses have to be treated as free parameters!!!

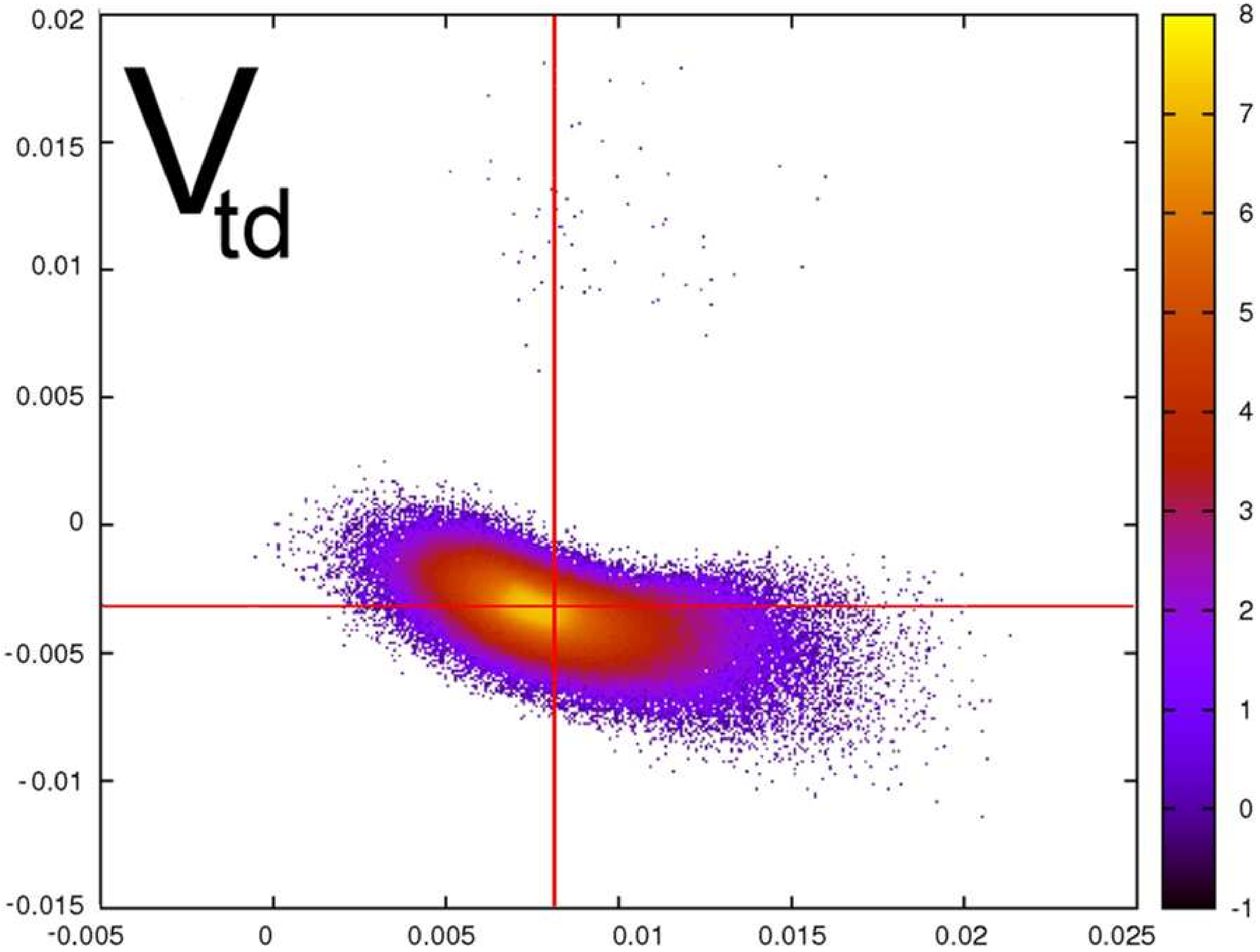
Bounds on the SM4 I

Allowed values: θ_{34} vs. θ_{24}



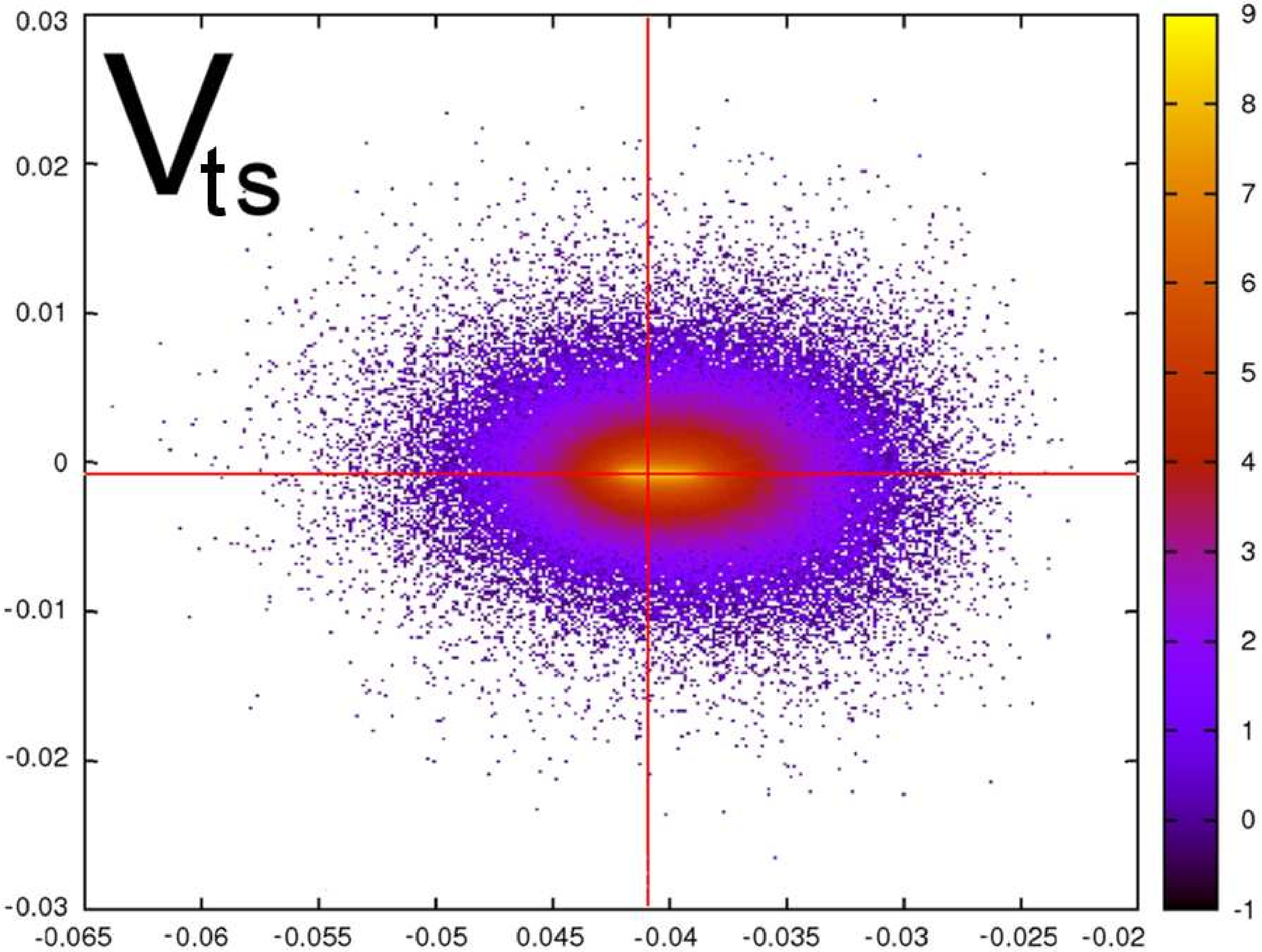
Bounds on the SM4 II

Allowed values: Im V_{td} vs. Re V_{td}



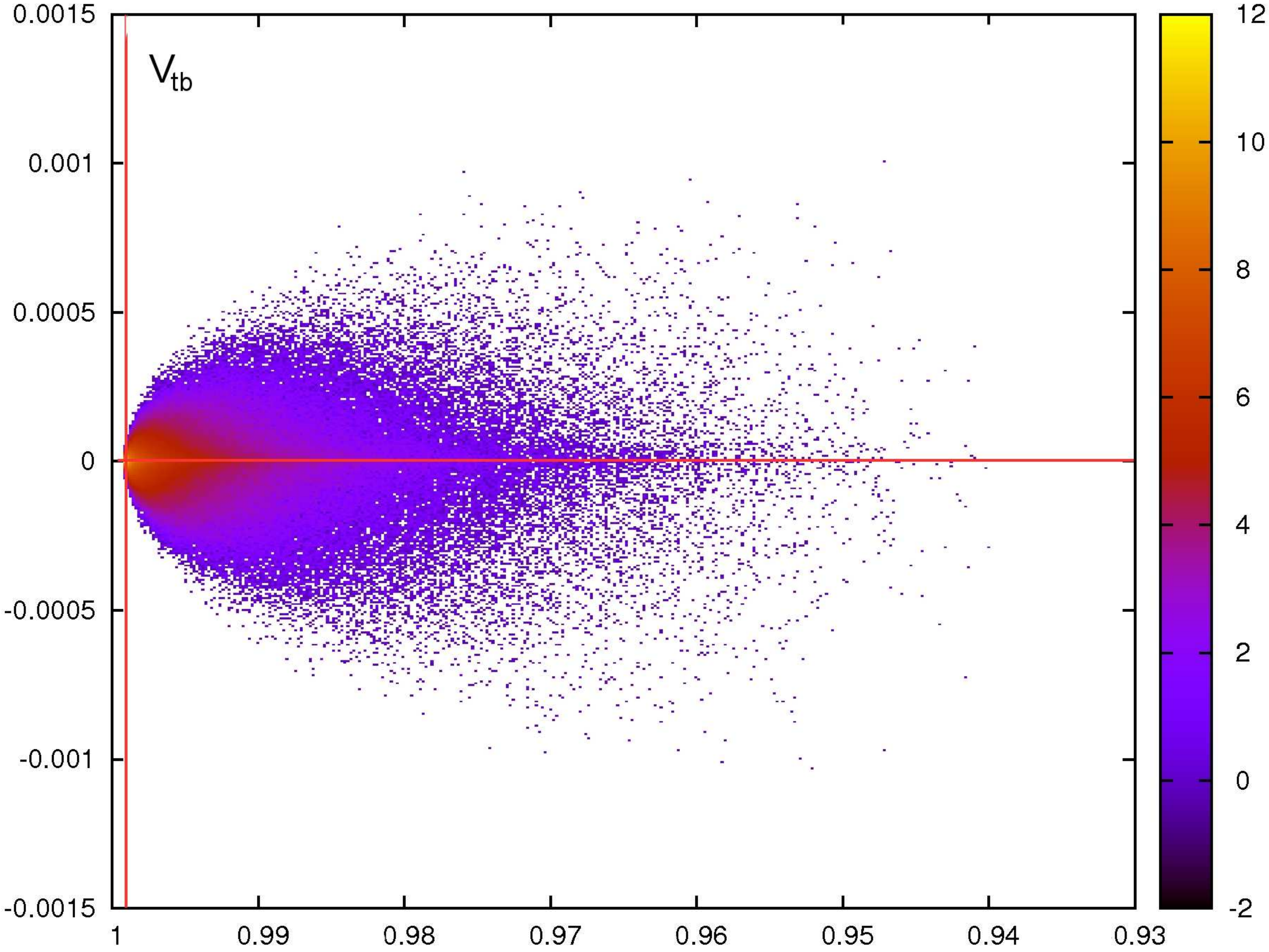
Bounds on the SM4 III

Allowed values: Im V_{ts} vs. Re V_{ts}



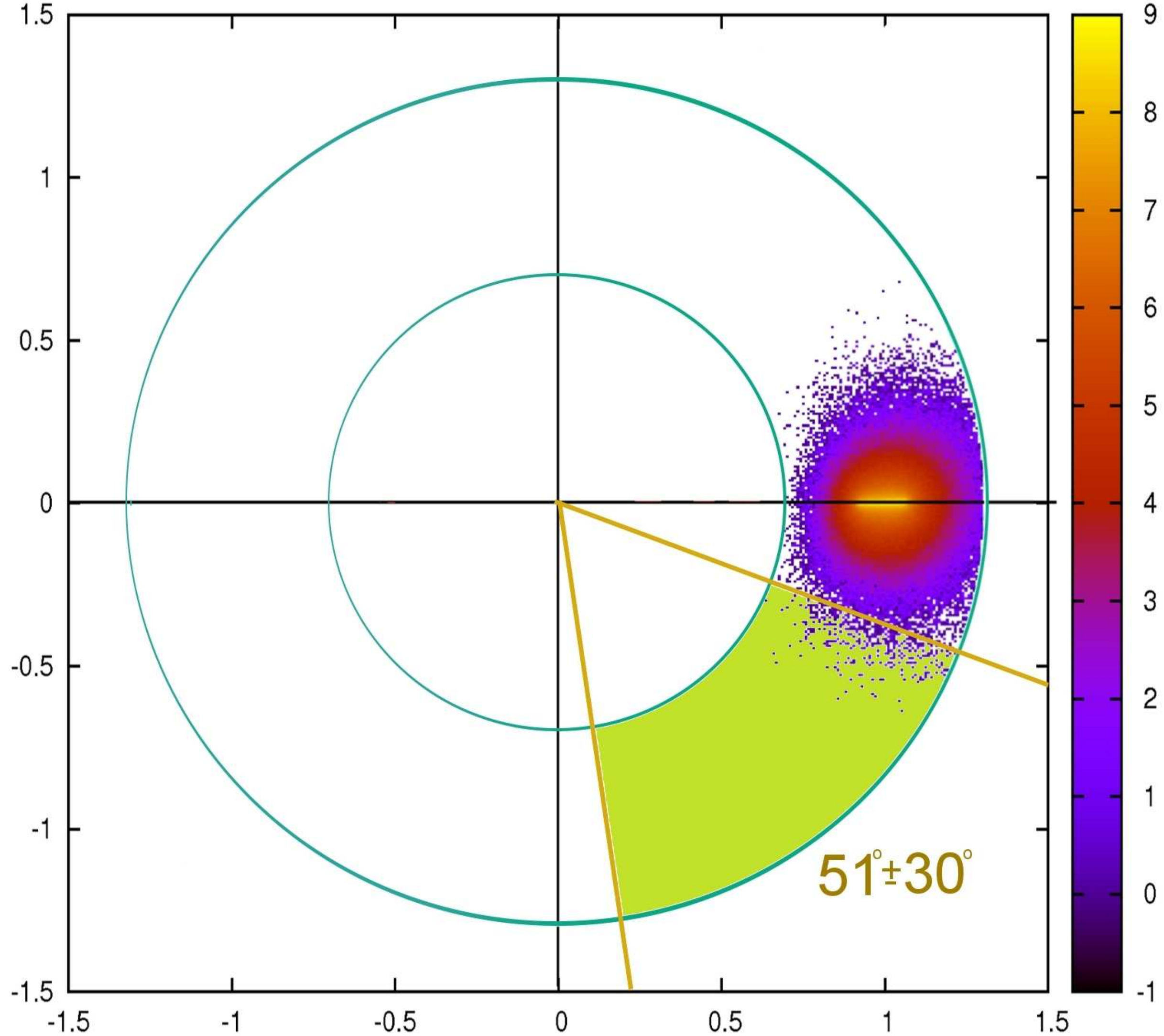
Bounds on the SM4 IV

Allowed values: Im V_{tb} vs. Re V_{tb}



New Physics in B_s Mixing = SM4?

Im Δ_{B_s} vs. Re Δ_{B_s}; $\Delta_{B_s} = \frac{M_{12}^{SM4,s}}{M_{12}^{SM4,s}}$



Outlook

SM is excluded by almost 4 σ and soon much more data (B_s-mixing, $B_s \to \mu^+\mu$, $\mu \to e\gamma$,...)

Test of the HQE with lifetimes

- τ_{B+}/τ_{B_d} and τ_{B_s}/τ_{B_d} look good, currently no hints for violations of duality
- more theoretical work necessary: perturbative and non-perturbative
- LHCb will provide precise lifetimes and lifetime difference

Precision determination of mixing observables

- $\Delta\Gamma_s/\Gamma_s$ agrees within large uncertainties
- high experimental precision in ΔM_s vs. sizeable non-perturbative uncertainties
- Evidence for new physics in CP-violation in mixing
- more theoretical work neccessary: perturbative and non-perturbative
- LHC: very precise mixing observables

An example for new physics: SM4 (non-MFV)

- More precise values needed for V_{cd}; V_{cs} (e.g. f_{D_s}, $D \to K$ form factors); V_{tb}
- SM4 Fit: Collaboration with CKMfitter
- SM4-Effects (Cancellations) more general e.g. WED
- Neutrino effects A.L., Päs, Schalla; 1010.3883; Dynamical symmetry breaking (talk by Sannino), ...
- LHC: find SM4 directly or exclude it via flavour observables