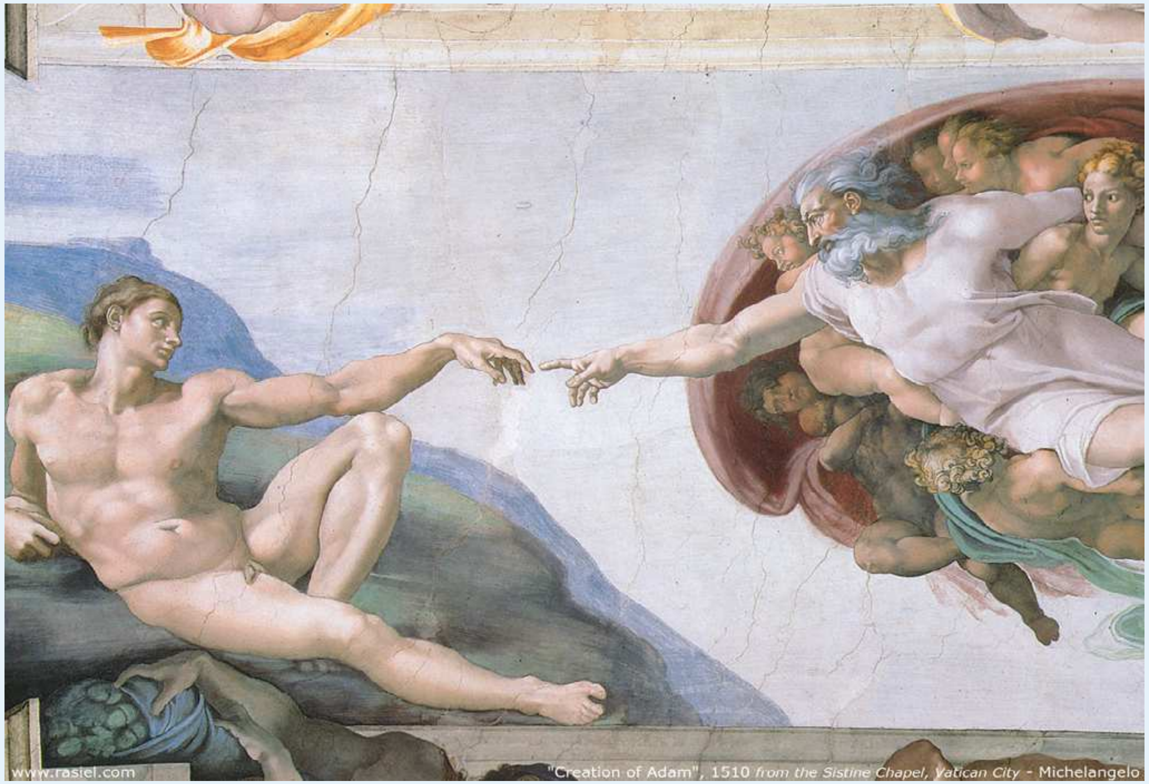
Selected Topics in Flavour Physics



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IPPP Durham

Outline

- Motivation for Flavour Physics
  - Search for the Origin of Matter in the Universe
  - Identify New Physics (NP) Effects
  - Constrain Models for New Physics
- Highlights - What did we really learn so far?
  - The SM rules
  - Test of our theoretical Tools
  - Still Space for sizable New Physics Effects
  - Several interesting Deviations are still there
- Some Roads to follow
  - Higher Precision necessary
  - New Observables in the Search for New Physics
- Conclusion

Flavour Physics

There are (at least) six kinds (=**flavours**) of quarks

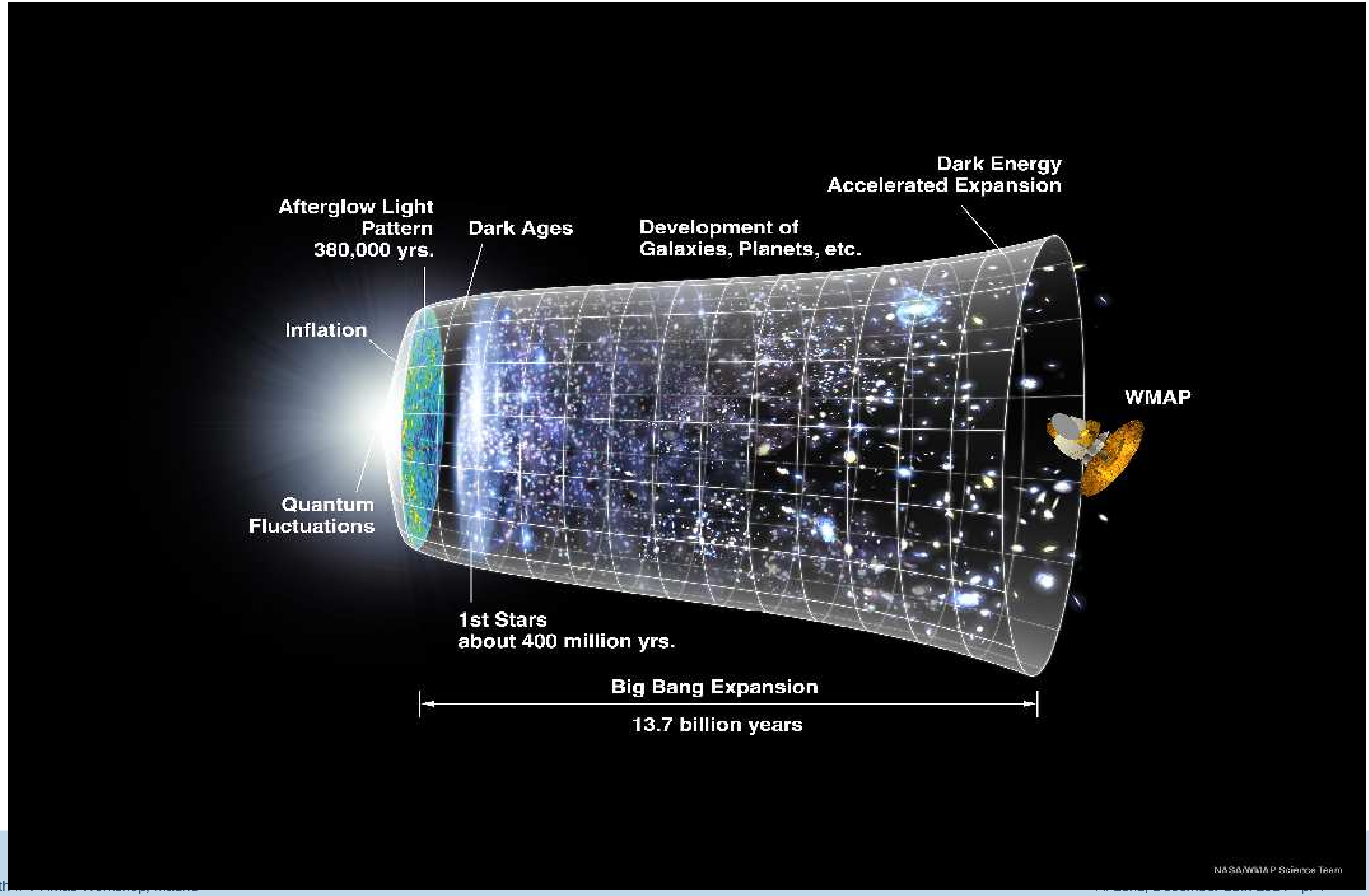
$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \begin{pmatrix} q = +2/3 \\ q = -1/3 \end{pmatrix}$$

- Proton p = $|uud\rangle$
- **(Heavy) Flavour Physics** describes hadrons with a charm- or a bottom-quark

	$D^0 = (\bar{u}c)$	$D^+ = (\bar{d}c)$	$D_s^+ = (\bar{s}c)$	$\Lambda_c = (udc)$
Mass (GeV)	1.86486	1.86962	1.96850	2.28646
Lifetime (ps)	0.4101	1.040	0.500	0.200

	$B_d = (\bar{b}d)$	$B^+ = (\bar{b}u)$	$B_s = (\bar{b}s)$	$B_c^+ = (\bar{b}c)$	$\Lambda_b = (udb)$
Mass (GeV)	5.27958	5.27926	5.3667	6.2745	5.6194
Lifetime(ps)	1.519	1.638	1.512	0.500	1.451

Motivation



Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

Motivation - Baryon Asymmetry

symmetric initial conditions
(Inflation: initial asymmetry is wiped out)

$$\Rightarrow N_{\text{matter}} = N_{\text{antimatter}}$$

But we exist and stars and...

Search for annihilation lines, nucleo synthesis, CMB,...

Motivation - Baryon Asymmetry

Search for annihilation lines, nucleo synthesis, CMB,...

Motivation - Baryon Asymmetry

Search for annihilation lines, nucleo synthesis, CMB,...

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \cdot 10^{-10}$$

How can this be created from symmetric initial conditions?

1967 Sakharov: The fundamental laws of nature must have several properties, in particular

CP-violation: Kaons: **1964 indirect (NP ’80), 1999 direct**

B_d: **2001 indirect, 2006 direct**

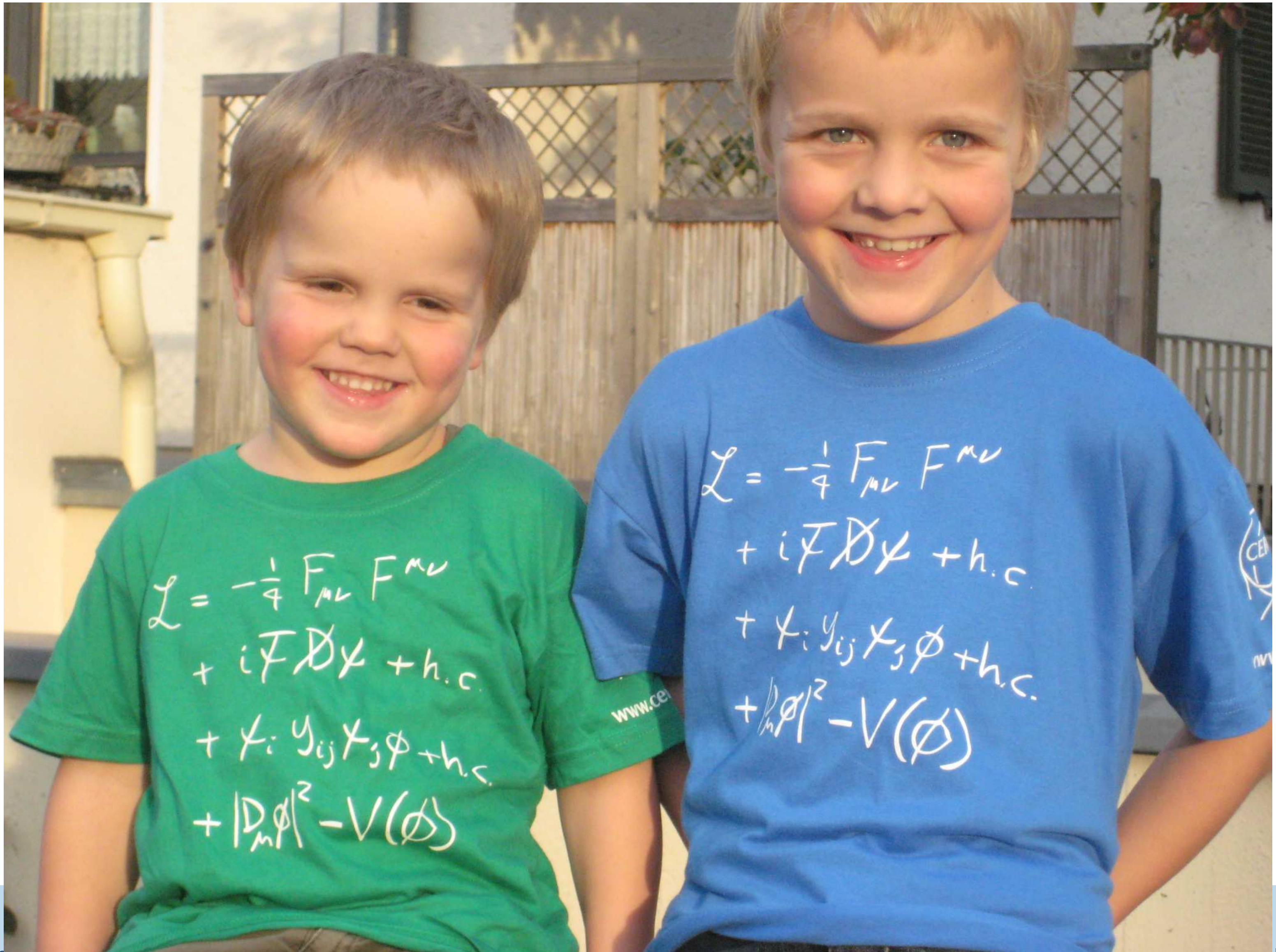
Charm: 2011 direct? (no indirect yet)

B^+: **2012 direct;** B_s: **2013 direct (no indirect yet)**

Can our fundamental theory cope with these requirements?

Motivation - Our fundamental Theory

The Standard Model = elegant description of nature at per mille precision



The Standard Model of Particle Physics

Matter (spin 1/2, fermions, 3 families)

Quarks (all interactions)

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{pmatrix} q = +2/3 \\ q = -1/3 \end{pmatrix}$$

Leptons (weak and em interaction)

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \quad \begin{pmatrix} q = 0 \\ q = -1 \end{pmatrix}$$

Forces (spin 1, bosons)

Interaction		M	R
Em	Photon γ	0	∞
Strong	Gluon g	0	$10^{-15} m$
Weak	$W^\pm, Z^0$	100 GeV	$10^{-18} m$

Proton $\equiv |uud\rangle, m_P = 1$GeV

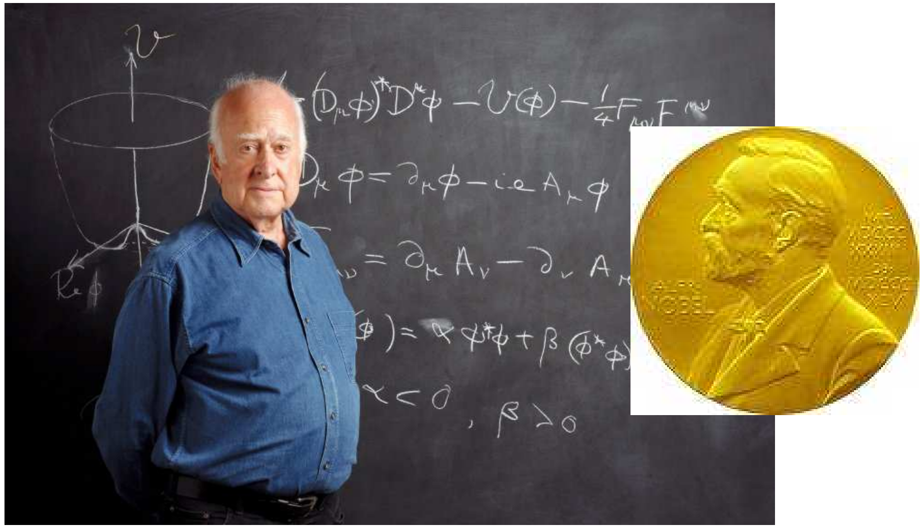
$n \to p + e^- + \bar{\nu}_e$

Generation of mass: Higgs particle h: (spin 0, boson), discovered 2012 at LHC by **ATLAS and CMS** $M_h = 125.7$ GeV

... Englert, Brout; Higgs; Guralnik, Hagen, Kibble; ...

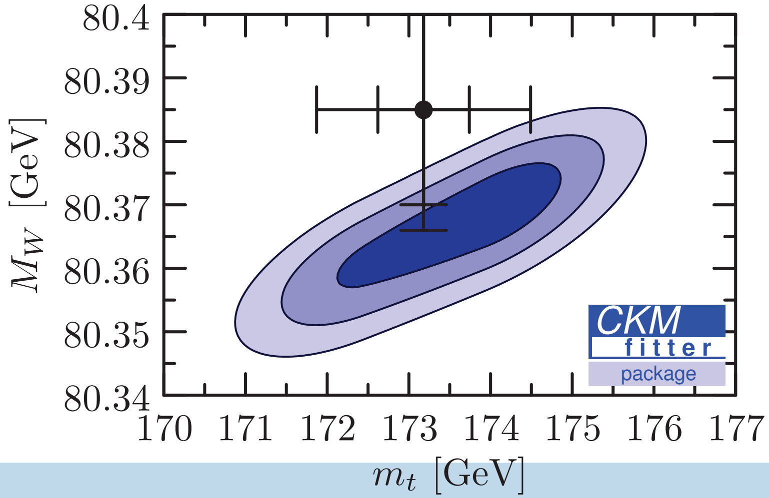
Motivation - Our fundamental Theory

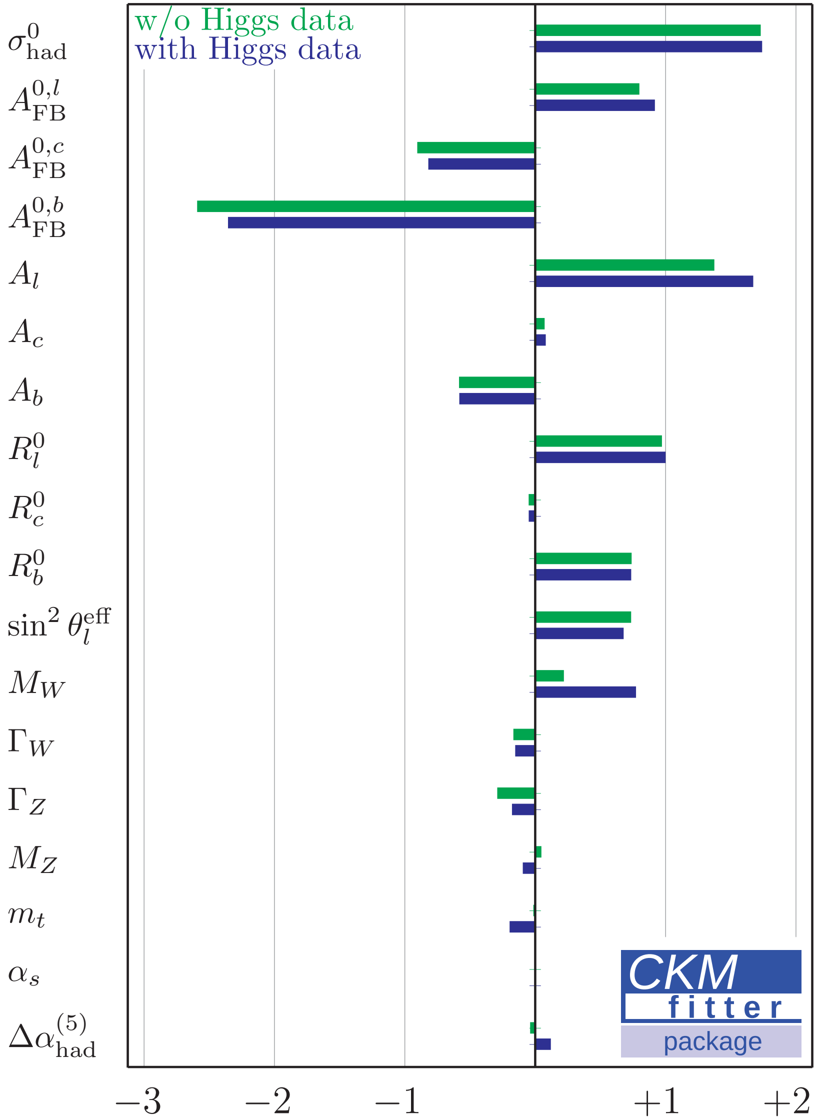
SM seems to be complete now - first electro-weak fit



Eberhardt et al., 1209.1101

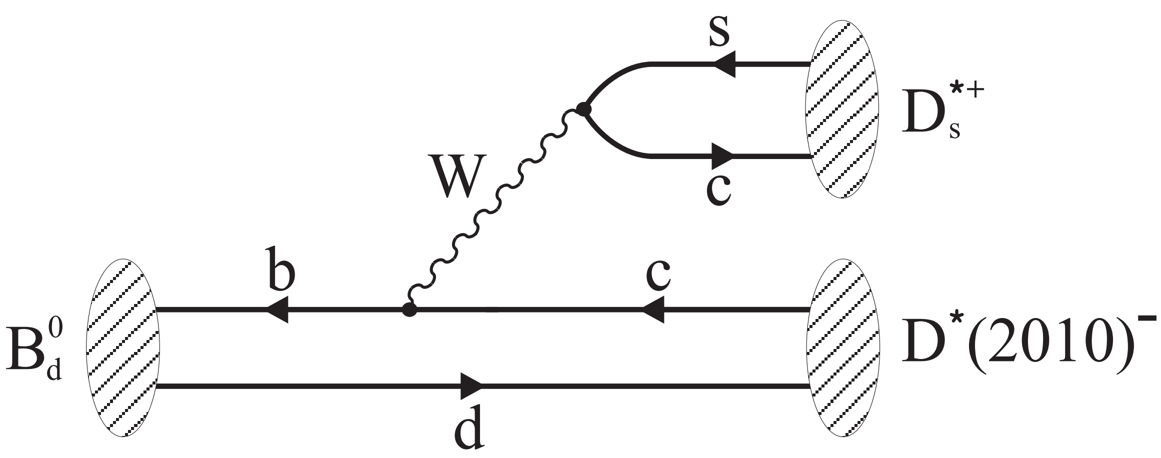
see also **GFitter 1209.2716**





Contains our fundamental Theory CP-violation?

The CKM matrix describes the coupling of quarks to the charged W-bosons



The amplitude of this decay is proportional to

$$\frac{g_2}{2\sqrt{2}} V_{cb}^* \cdot ... \cdot \frac{g_2}{2\sqrt{2}} V_{cs}$$

An imaginary part of the CKM elements is equivalent to CP violation!

V_{ub} **and** V_{td} **have most "space" for an imaginary part; both appear in B-meson decays**

Motivation - Our fundamental Theory

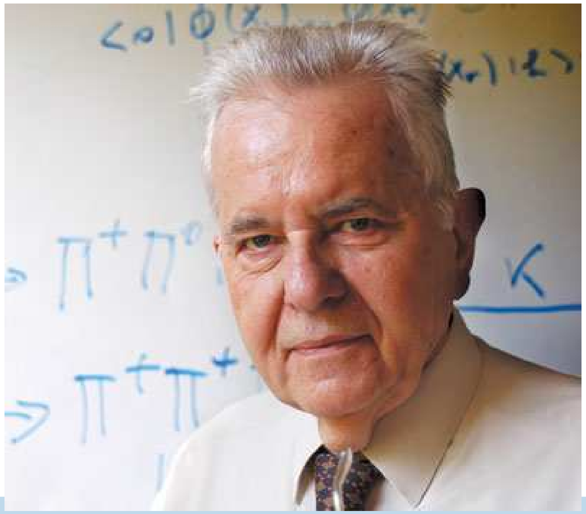
Implementation of CP violation in the CKM matrix - need at least 3 families

1972 only u,d and s known, **Kobayashi and Maskawa** postulated six quarks!

$$
|V_{CKM}| = \begin{pmatrix}
0.974235^{+0.000080}_{-0.000158} & 0.22551^{+0.00068}_{-0.00034} & 0.00357^{+0.00016}_{-0.00015} \\
0.22537^{+0.00068}_{-0.00035} & 0.973395^{+0.000095}_{-0.000176} & 0.04136^{+0.00071}_{-0.00128} \\
0.00855^{+0.00018}_{-0.00030} & 0.04062^{+0.00070}_{-0.00125} & 0.999138^{+0.000052}_{-0.000030}
\end{pmatrix}
$$

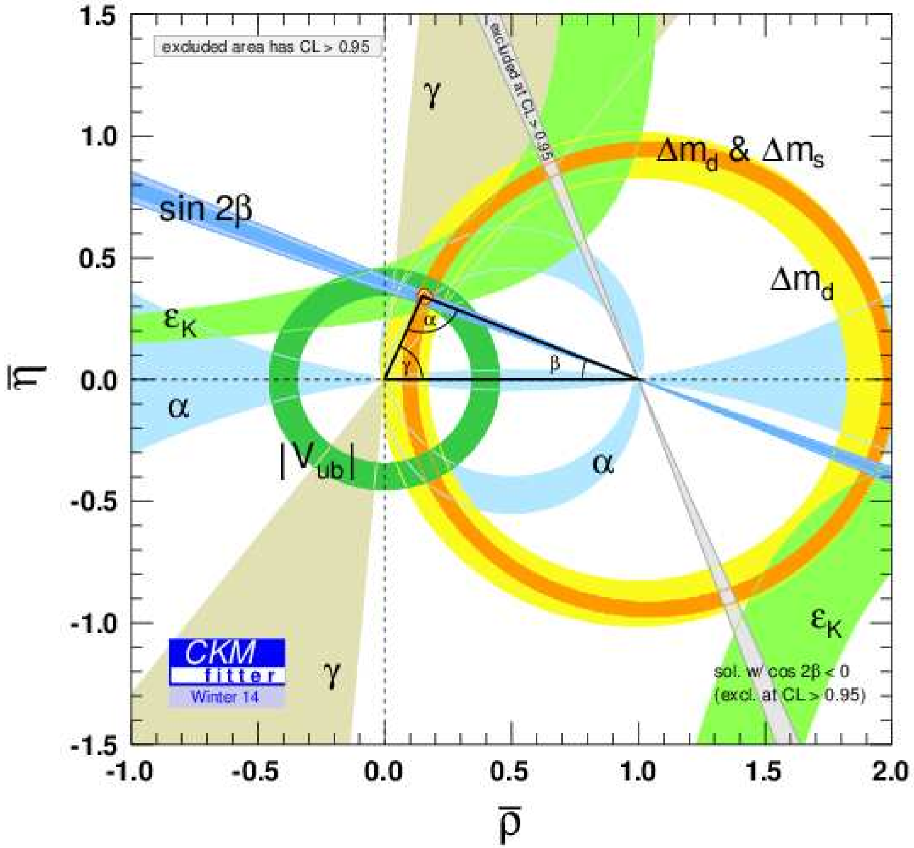
CP (crossed out)

Fit from **CKMfitter 2014**, see also **UTfit ...**



NP 2008

Motivation - CKM works perfect



CKMfitter, UT fit
Lunghi,Soni,Laiho
Eigen et al...

But amount of CP violation seems to be too small for baryon asymmetry

$$\frac{J}{(100\,\text{GeV})^{12}} \approx 10^{-20}$$

Better look in the lepton sector?

Open Questions in the SM

The SM is extremely successful, but it leaves many **questions** unanswered:

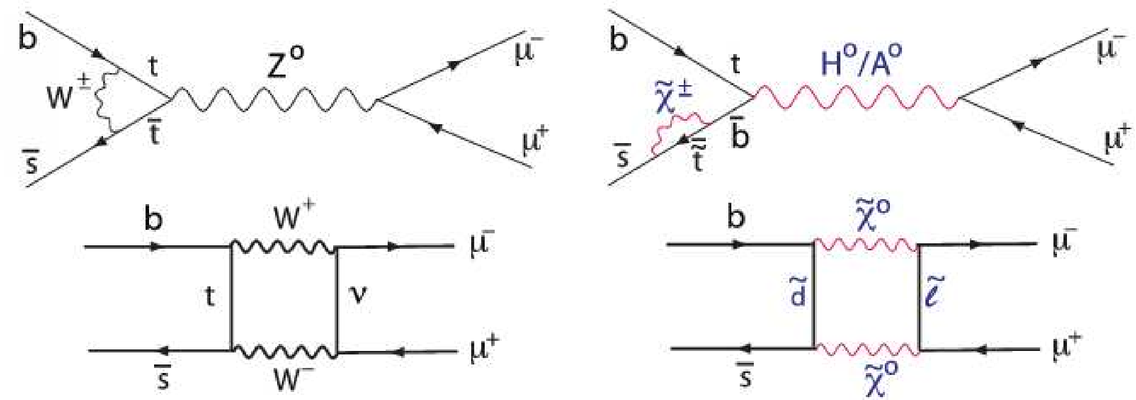
- What is dark matter?
- What is dark energy?
- How is gravity quantised?
- Why are there 3 families of particles?
- How was matter created in the universe?
  CP-violation in the SM is not sufficient!
- ...

Search for new physics:

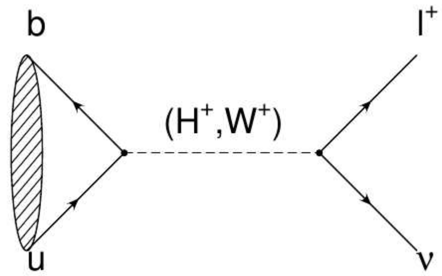
- **Motivated by theory:** “Model-building”
- **Motivated by experiment:** Direct search for new effects
- **Motivated by phenomenology:** Search for Deviations from precise SM predictions

Why Flavour Physics?

- **CP violation** till now only found in quark flavour physics
- **Theoretically clean:** $\alpha_s(m_b) \approx 0.2 \approx \Lambda/m_b$
- many processes strongly suppressed in the SM due to quantum corrections:
  - $B_s \to \mu\mu$ or $b \to s\gamma$: **F**lavor **C**hanging **N**eutral **C**urrents



  - But also: $B \to \tau\nu$,...



Strong constraints on many NP models

- **Many experiments**, e.g. **LHCb, ATLAS, CMS; Super-Belle, Panda, LINAC, TLEP,...**

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  - The SM rules
  - Test of our theoretical Tools
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The SM rules

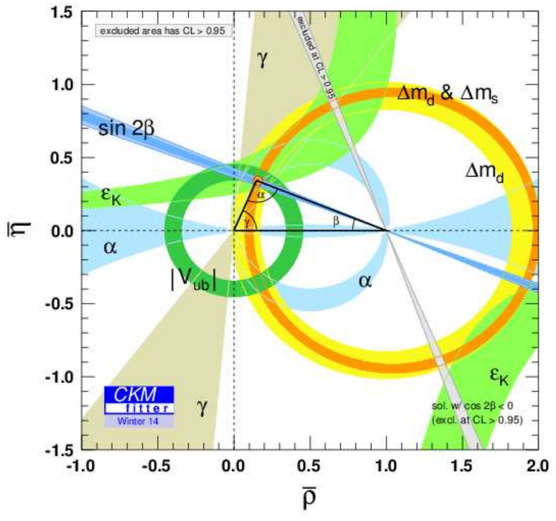
- Huge # of flavour observables are **SM-like**, e.g. lifetimes, hadronic decays,...
- Unitarity triangle is SM like **HFAG, CKMfitter (at CKM 2014), UTfit**

$$\sin 2\beta^{direct} = 0.679 \pm 0.020 \qquad \gamma^{direct} = \left(73.2^{+6.3}_{-7.0}\right)^\circ$$
$$\sin 2\beta^{indirect} = 0.774^{+0.017}_{-0.036} \qquad \gamma^{indirect} = \left(66.4^{+1.3}_{-2.5}\right)^\circ$$

There is still space for sizable NP effects

- **Even very rare processes are SM-like, e.g.**
  - $B_s \to \mu\mu$
  - $b \to s\gamma$
  - **B-mixing:** ΔM_q, $\Delta\Gamma_s$, a_{sl}^q
  - **...**

There is still space for sizable NP effects



The SM rules: $B_s \to \mu\mu$

CMS **1307.5025** $(4.3\sigma, 25 fb^{-1})$ and **LHCb** **1307.5024** $(4.0\sigma, 3 fb^{-1})$

$$
\begin{aligned}
Br(B_s \to \mu\mu) &= (2.8^{+0.7}_{-0.6}) \cdot 10^{-9} \quad \textbf{1411.4413}\ (6.2\sigma) \\
Br(B_d \to \mu\mu) &= (3.9^{+1.6}_{-1.4}) \cdot 10^{-10} \quad \textbf{1411.4413}\ (3.2\sigma)
\end{aligned}
$$

agrees with the SM prediction - **huge success of the SM**

$$
\begin{aligned}
Br(B_s \to \mu\mu) &= 3.65 \pm 0.23 \cdot 10^{-9} \quad \textbf{Bobeth et al. 1311.0903} \\
Br(B_d \to \mu\mu) &= 1.06 \pm 0.09 \cdot 10^{-10} \quad \textbf{Bobeth et al. 1311.0903}
\end{aligned}
$$

Remark: SM prediction depends on value of V_{cb} Buras; Knegjens

There is still space for sizable NP effects

The SM rules: B-mixing

Mixing is a common effect in particle physics!
(interaction eigenstate $\neq$ mass eigenstate)

- "Unification" of electromagnetic and weak interaction
- Neutrino oscillations
- Quark mixing via the CKM matrix
- Mixing of neutral mesons - macroscopic quantum effect!

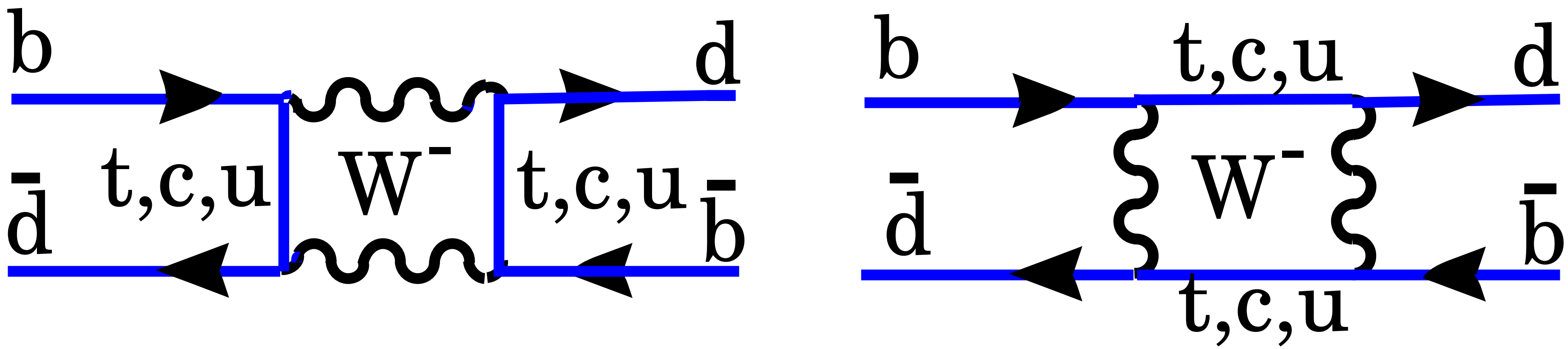
It was observed in

- K^0-system: 1950s (see text books, regeneration...)
- B_d-system: 1986 ΔM_d; ??? $\Delta \Gamma_d$
- B_s-system: 2006 ΔM_s; 2012 $\Delta \Gamma_s$
- D^0-system: 2007, 2012 $\Delta M_D, \ \Delta \Gamma_D$

Strongly suppressed in the SM (higher order in weak interaction)
New physics effects might be of comparable size

?Is QCD under control?

The SM rules: B-mixing



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

- **Mass difference:** $\Delta M := M_H - M_L \approx 2|M_{12}|$ **(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. $B_q \to Xl\nu$ (*semi-leptonic*)

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

The SM rules: B-mixing

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

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

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

- Perfect agreement with SM
- Important bounds on the unitarity triangle and NP
- **Dominant SM uncertainty = Lattice**

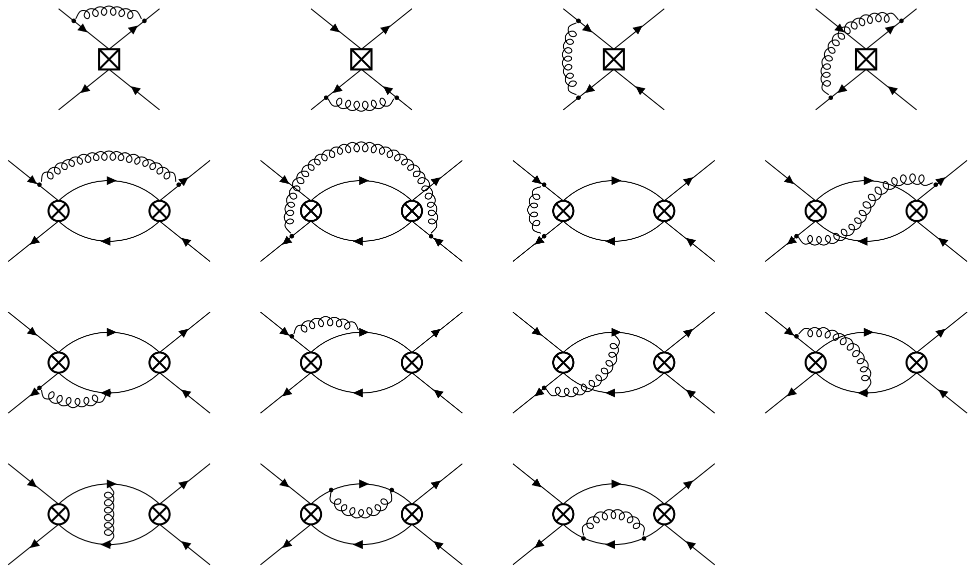
There is still space for sizable NP effects

Test of our theoretical Tools

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



Test of our theoretical Tools

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)

Test of our theoretical Tools

(Almost) all discrepancies disappeared:

- ’12: $n_c^{\rm 2011PDG} = 1.20 \pm 0.06$ vs. $n_c^{\rm SM} = 1.23 \pm 0.08$ **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

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

$\Rightarrow$ 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: Lattice + NNLO-QCD

Test of our theoretical Tools

Finally $\Delta\Gamma_s$ is measured! E.g. from $B_s \to J/\psi\phi$

LHCb Moriond 2012, 2013, 2014; ATLAS; CMS; CDF; DO

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

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 Tools

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)
- Quark hadron duality works: theoreticians fought for 35 years

How precise does it work? 20%? 10%?

Still more accurate predictions and data needed!

LHCb, ATLAS, CMS?, TeVatron, Super-Belle

1. **Apply HQE also to $b \to c\bar{c}s$ transitions and lifetimes**
2. **Apply HQE to quantities that are sensitive to NP**
3. **Apply HQE also to quantities in the charm system?**
4. **Do lattice determination $\&$ NNLO-QCD**, in progress, e.g. **FNAL/MILC; HPQCD**

The SM rules: Lifetimes Summary

$$\frac{\tau(B_s)}{\tau(B_d)}^{\rm SM} = 1.001 \pm 0.002 \qquad \frac{\tau(B_s)}{\tau(B_d)}^{\rm Exp} = 0.995 \pm 0.006$$

$$\frac{\tau(B^+)}{\tau(B_d)}^{\rm SM} = 1.04^{+0.05}_{-0.01} \pm 0.02 \qquad \frac{\tau(B^+)}{\tau(B_d)}^{\rm Exp} = 1.076 \pm 0.004$$

$$\frac{\tau(\Lambda_b)}{\tau(B_d)}^{\rm SM} = 0.935 \pm 0.054 \qquad \frac{\tau(\Lambda_b)}{\tau(B_d)}^{\rm Exp} = 0.955 \pm 0.009$$

$$\frac{\bar\tau(\Xi_b^0)}{\bar\tau(\Xi_b^+)}^{\rm SM} = 0.94 \pm 0.04 \pm ??? \qquad \frac{\tau(\Xi_b^0)}{\tau(\Xi_b^-)}^{\rm Exp} = 0.924 \pm 0.035$$

$$\frac{\bar\tau(\Xi_b^0)}{\tau(\Lambda_b)}^{\rm SM} \approx 1 \qquad \frac{\tau(\Xi_b^0)}{\tau(\Lambda_b)}^{\rm Exp} = 1.006 \pm 0.018 \pm 0.010$$

$$\frac{\tau(\Lambda_b)}{\bar\tau(\Xi_b^+)}^{\rm SM} = 0.95 \pm 0.06 \pm ??? \qquad \frac{\tau(\Lambda_b)}{\tau(\Xi_b^-)}^{\rm Exp} = 0.918 \pm 0.026 \pm 0.011$$

Theory: **AL 1405.3601**

Exp.: **HFAG 2014, LHCb 1405.7223, 1409.8568**

The SM rules: improved Predictions

All lifetime predictions are **strongly limited** by our knowledge of the hadronic matrix elements of 4-quark operators

List of lattice predictions:

- $\tau(B^+)/\tau(B_d)$: **Becirevic, hep-ph/0110124**
- $\tau(\Lambda_b)/\tau(B_d)$: **DiPierro, Sachrajda, Michael, 1999** - **Exploratory study**
- $\tau(\Xi_b^0)/\tau(\Xi_b^+)$: **UNKNOWN**
- $\tau(D^+)/\tau(D^0)$: **UNKNOWN**
- ...

Typical form of the 4-quark operators:

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

Also colour-octett, and S-P,...

The SM rules: semi-leptonic Asymmetries

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

$$a_{fs}^s = (1.9 \pm 0.3) \cdot 10^{-5}, \qquad a_{fs}^d = -(4.1 \pm 0.6) \cdot 10^{-4},$$

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

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

Experimental bounds: HFAG 14; D0,1106.6308

$$a_{fs}^s = -(77 \pm 42) \cdot 10^{-4} \qquad a_{fs}^d = -(9 \pm 21) \cdot 10^{-4}$$

$$A_{sl}^b = -(7.87 \pm 1.72 \pm 0.93) \cdot 10^{-3} \qquad \left| \frac{\Delta \Gamma_d}{\Gamma_d} \right| = (1 \pm 10) \cdot 10^{-3}$$

$$\phi_s^{c\bar{c}s} = -2\beta_s = 0.00 \pm 0.07$$

There is still room for sizable deviations

The SM rules

Model independent analysis: **A.L., Nierste, '06**

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

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

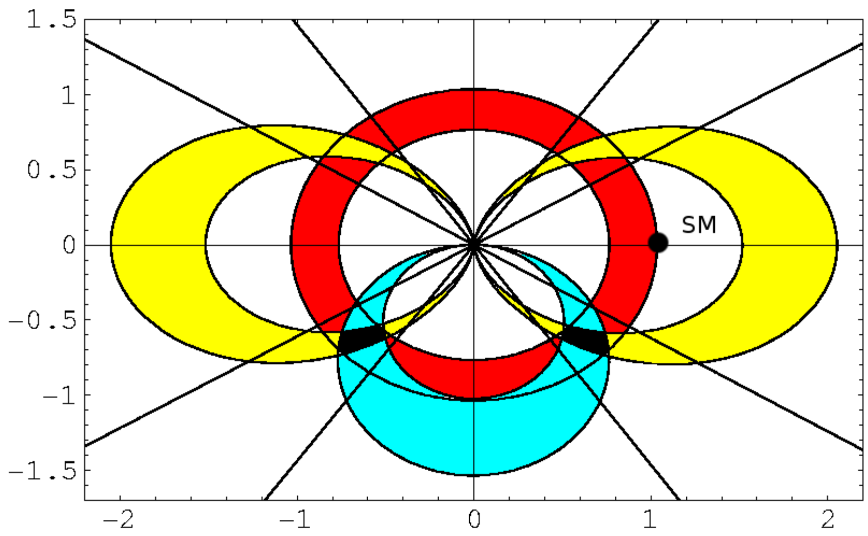
$$\Delta\Gamma_s = 2|\Gamma_{12,s}|\cdot\cos\left(\phi_s^{\rm SM}+\phi_s^\Delta\right)$$

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

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

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

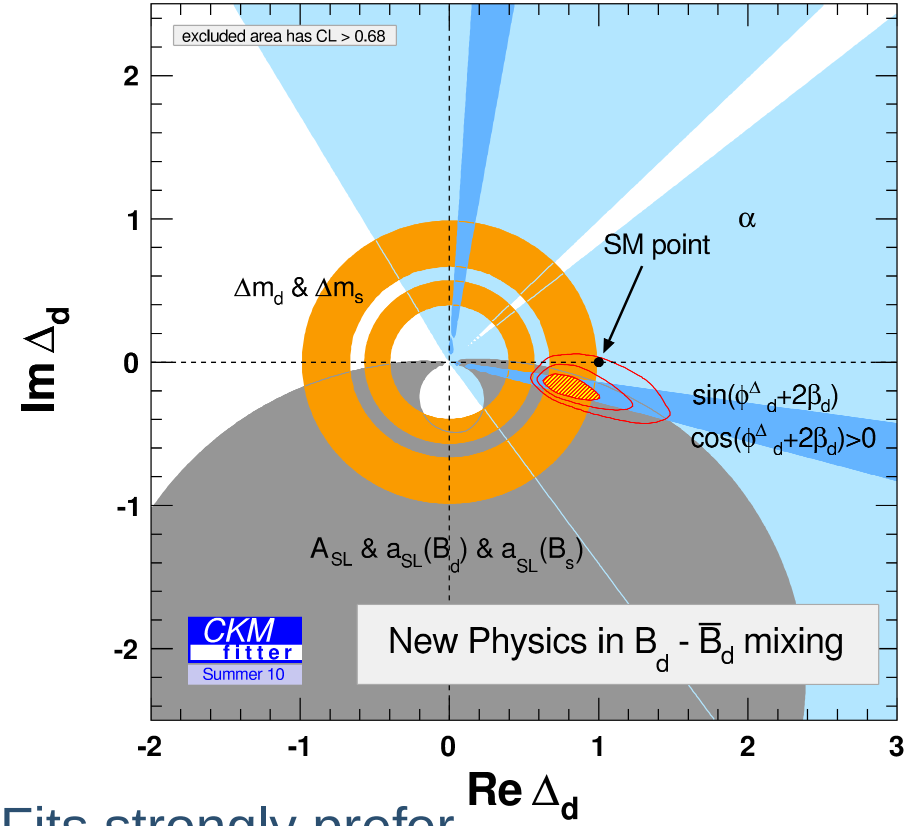
For $|\Delta_s| = 0.9$ and $\phi_s^\Delta = -\pi/4$ one gets the following bounds in the **complex Δ-plane**:

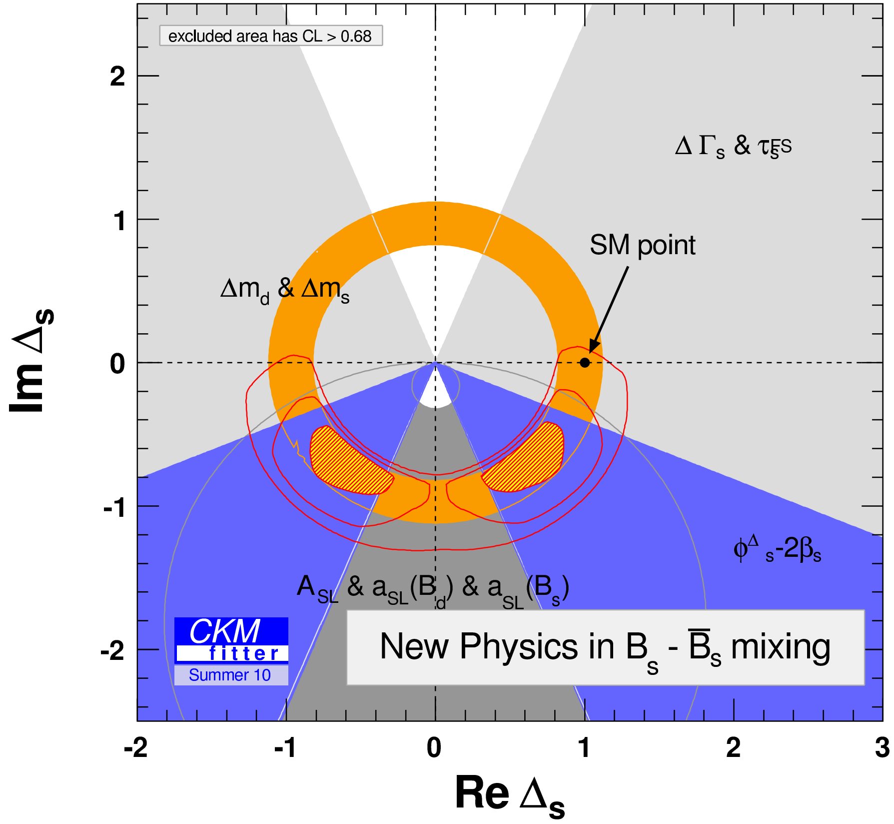


The SM rules not!!!

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

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





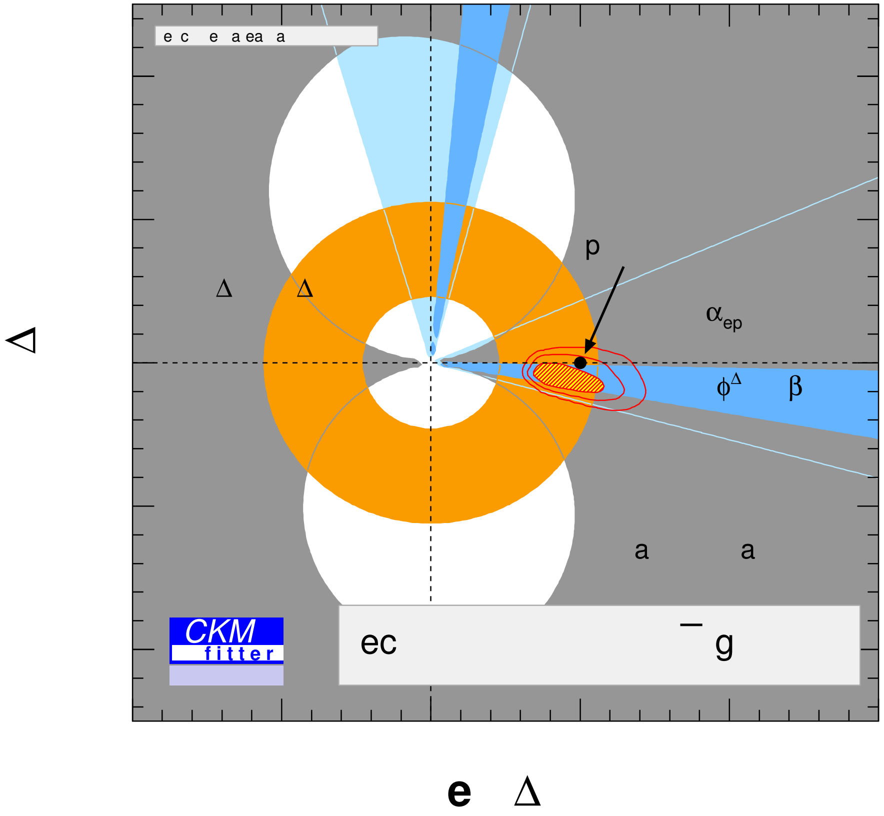
Fits strongly prefer

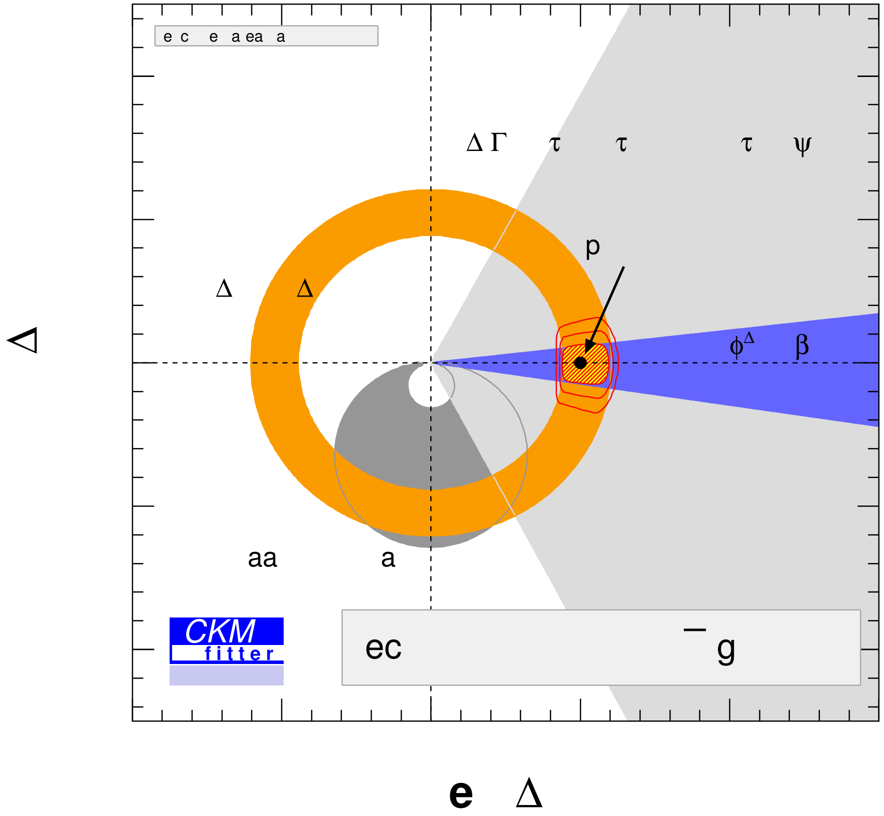
- **large new physics effects in the B_s-system**
- **some new physics effects in the B_d-system**

The SM rules

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 some sizable space for NP effects**

Deviations - Overview

1. Huge $\#$ of flavour observables are **SM-like**
2. **Still some sizable space for NP effects**
3. **There are several interesting deviations in the present data**

- **Tree-level observables**
  - V_{ub} and V_{cb} - about 3 σ
  - $B \to \tau\nu$ - about 2 σ
  - Lepton universality: $R(D^{(*)})$ - 3.4 σ
  - direct/indirect determination of the CKM angle γ
- **Loop-induced observables**
  - direct/indirect determination of the CKM angle β; about 2 σ
  - The dimuon asymmetry - about 3 σ
  - $B \to K^{(*)} ll$ - Br, P_5' up to 4 σ
  - $B_s \to \phi ll$ - Br
  - Lepton universality: $Br(B^+ \to K^+ \mu\mu)/Br(B^+ \to K^+ ee)$ deviates by 2.6 σ
  - $Br(B_d \to \mu\mu)/Br(B_s \to \mu\mu)$ deviates by 2.3 σ **1411.4413**
- **Observables in the Charm-sector**
  - CPV in D-decays?

Deviations: V_{ub}

Exclusive	$\vert V_{ub}\vert = 0.00323 \pm 0.00031$
Inclusive	$\vert V_{ub}\vert = 0.00441 \pm 0.00021$
$B \to \tau\nu$	$\vert V_{ub}\vert = 0.00504 \pm 0.00064$
Fit	$\vert V_{ub}\vert = 0.00357 \pm 0.00015$

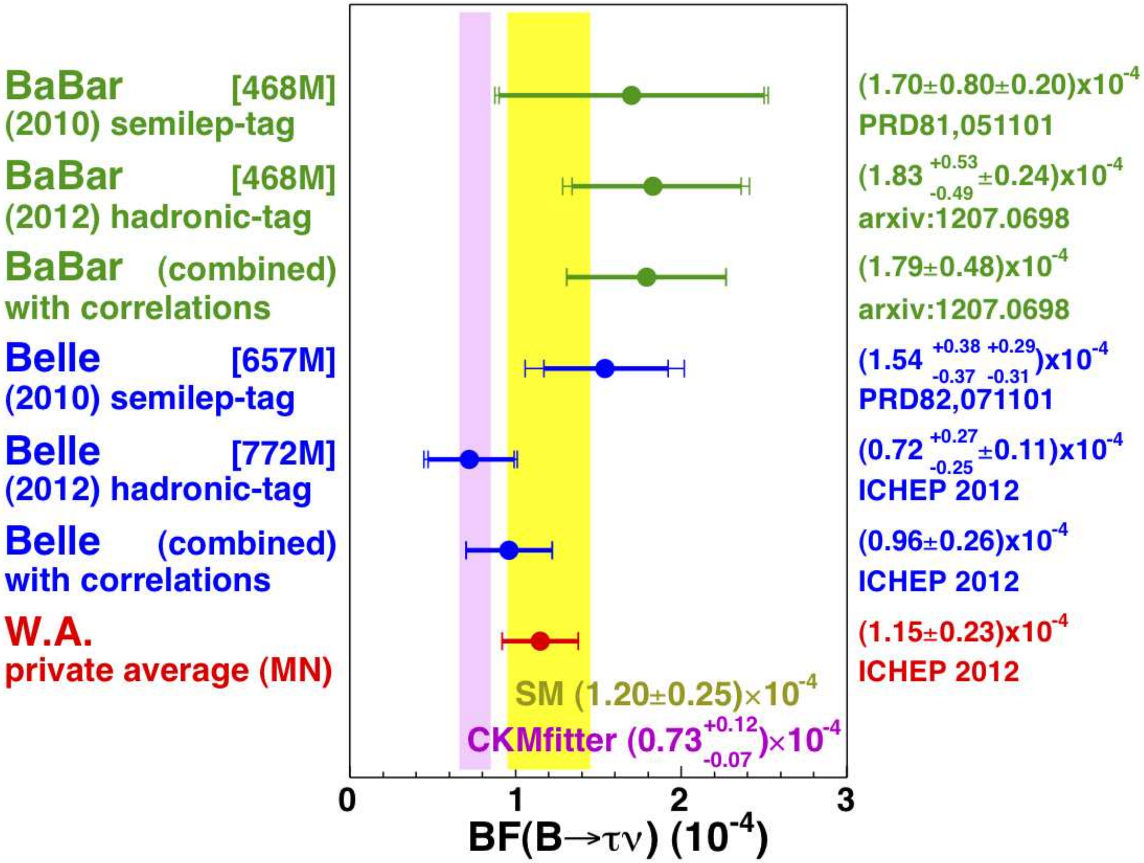
HFAG; HPQCD 2007; MILC Fermilab 2008;Ball/Zwicky 2005; Lange/Neubert/Paz 2005; Andersen/Gardi 2006,2008; Gambino/Giordano/Ossola/Uraltsev 2007; Aglietti/Di Lodovico/Ferrera/Ricciardi 2009; Aglietti/Ferrera/Ricciardi 2007; Bauer/Ligeti/Luke 2001,...

- V_{ub} is actually of order λ^4 and not λ^3: $0.00355 = (0.22457)^{3.77673}$
- Hadronic uncertainties (lattice, LCSR) underestimated?
- **Soni and Lunghi:** do not to use V_{ub} in the global fit
- **Crivellin0907.2461; Buras/Gemmler/Isidori 1007.1993:** RH currents $\Rightarrow$ *incl.* $\neq$ *excl.*
- New Physics in $B \to \tau\nu$ vs. B_d-mixing

see e.g. **G. Ricciardi, Dec 2014, talk in Pisa**

Deviations: $B \to \tau\nu$

New results from Belle **1208.4678** confirm the SM (new BaBar still large?)



Is there a similar problem in $B \to D^{(*)}\tau\nu$? **BaBar 1303.0571, Belle preli.** or also hadronic uncertainties **Becirevic et al 1206.4977**

Deviations: Di-muon Asymmetry

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

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}? $\rightarrow$ 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**

Deviations: Di-muon Asymmetry

- New measurements for the individual semi leptonic CP asymmetries

$a_{sl}^d = -0.39 \pm 0.35 \pm 0.19\%$	**BaBar 1411.1842**
$a_{sl}^d = -0.02 \pm 0.19 \pm 0.30\%$	**LHCb 1409.8586**
$a_{sl}^s = -0.06 \pm 0.50 \pm 0.36\%$	**LHCb 1308.1048**
$a_{sl}^s = -1.12 \pm 0.74 \pm 0.17\%$	**D0 1207.1769**
$a_{sl}^d = +0.68 \pm 0.45 \pm 0.14\%$	**D0 1208.5813**
$a_{sl}^d = +0.06 \pm 0.17^{+0.38}_{-0.32}\%$	**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**

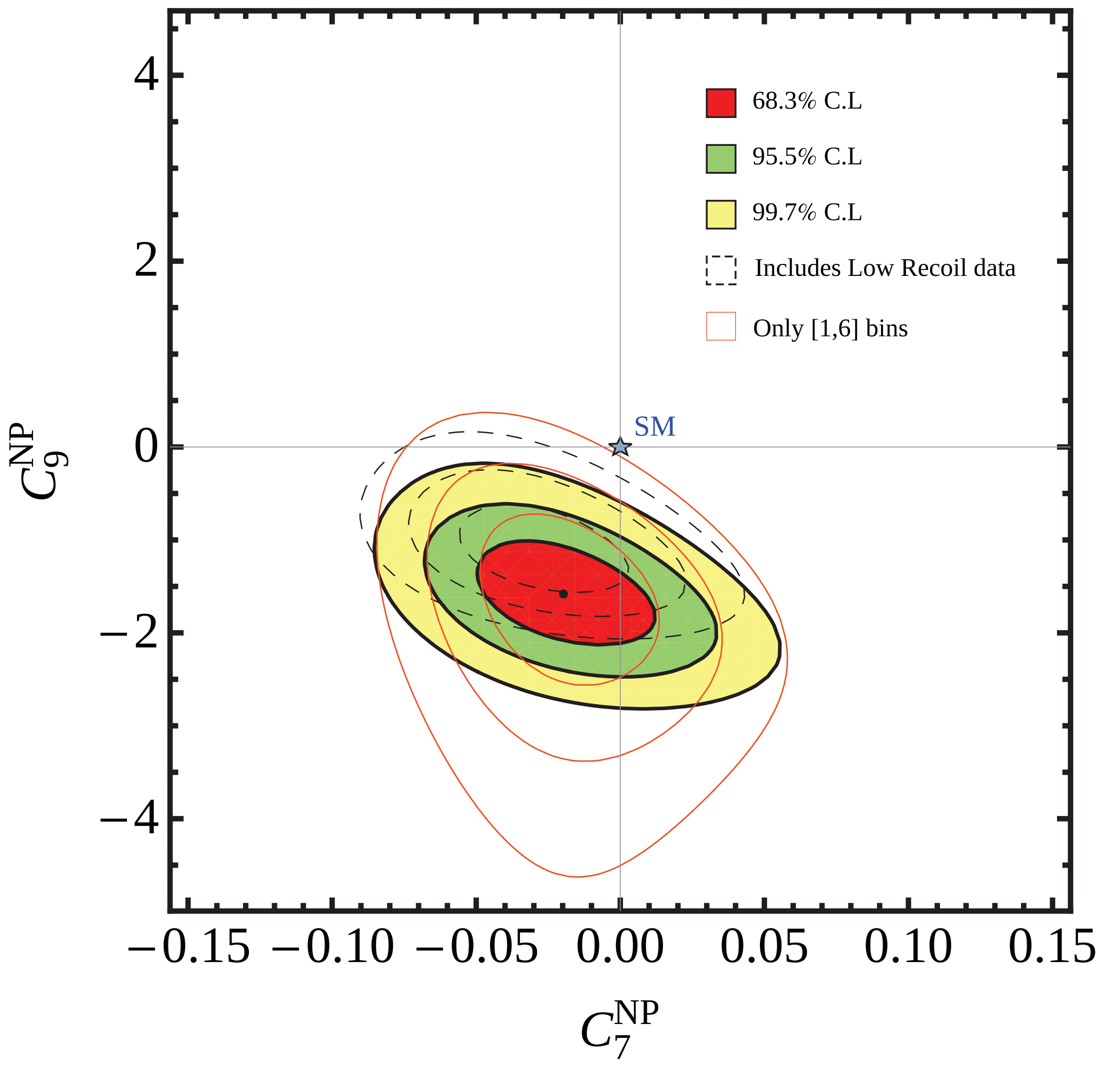
$$A_{sl}^b = C_d a_{sl}^d + C_s a_{sl}^s + C_\Gamma \frac{\Delta\Gamma_d}{\Gamma_d} + ???$$ (e.g. Nierste CKM2014; AL et al.)

There is still space for sizable NP effects in $\Delta\Gamma_d$

Deviations: Fit of FCNC processes

Fits of penguins via $B_s \to \mu\mu$, $B \to K^{(*)}ll$, $b \to s\gamma$,...

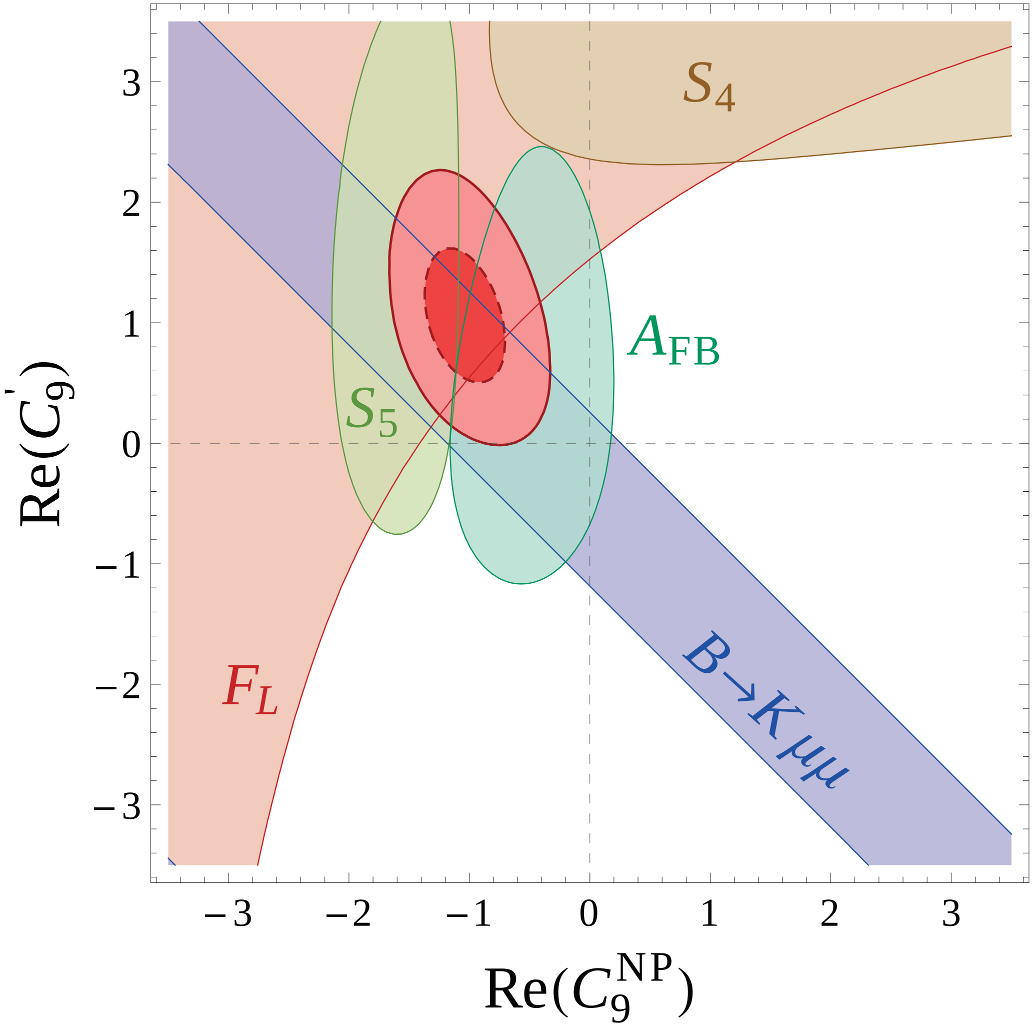
1. **Descotes-Genon, Matias, Virto - 1307.5683**



Deviations: Fit of FCNC processes

Fits of penguins via $B_s \to \mu\mu$, $B \to K^{(*)}ll$, $b \to s\gamma$,...

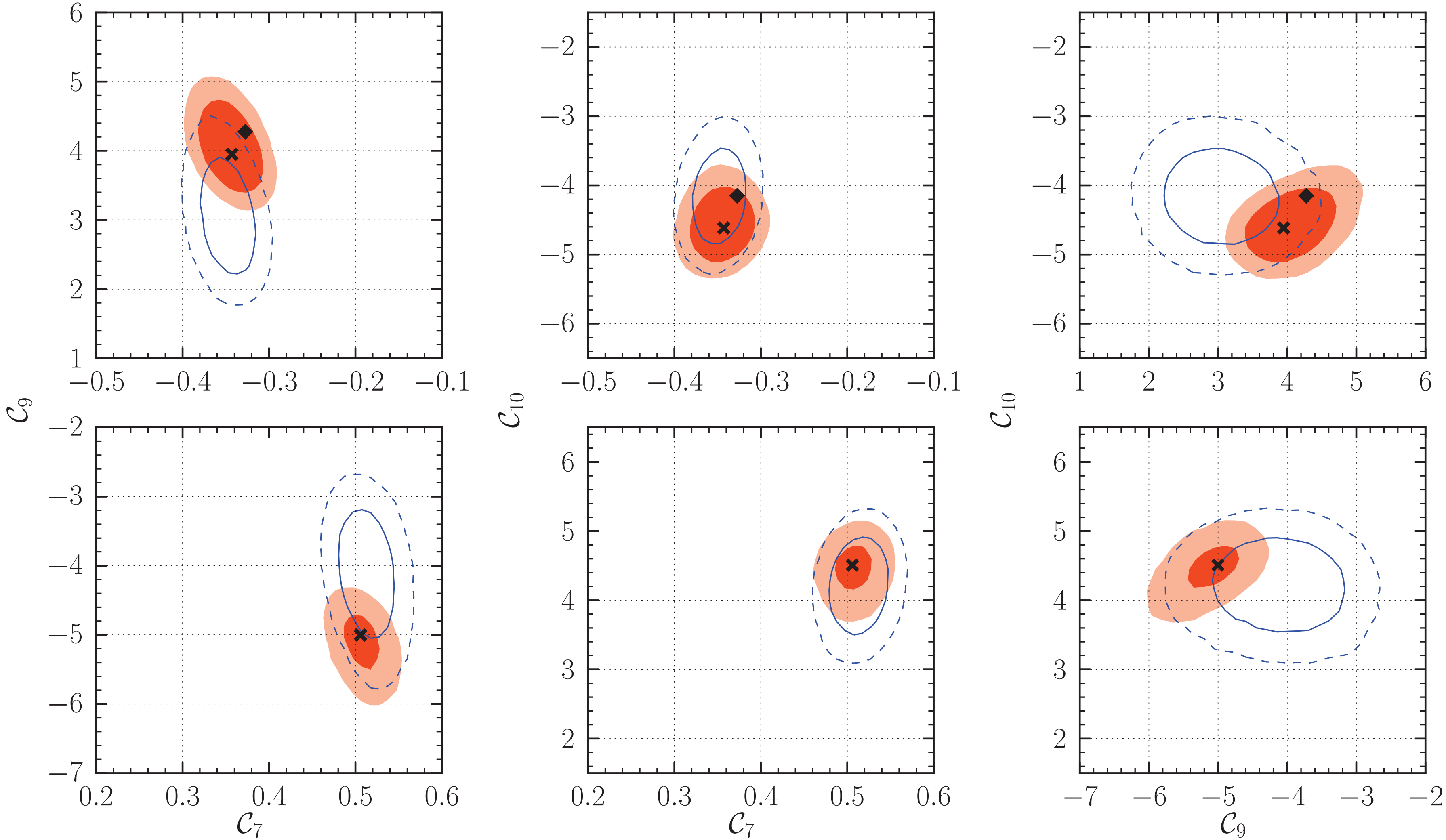
2. **Altmannshofer, Straub - 1308.1501**



Deviations: Fit of FCNC processes

Fits of penguins via $B_s \to \mu\mu$, $B \to K^{(*)} ll$, $b \to s\gamma$,...

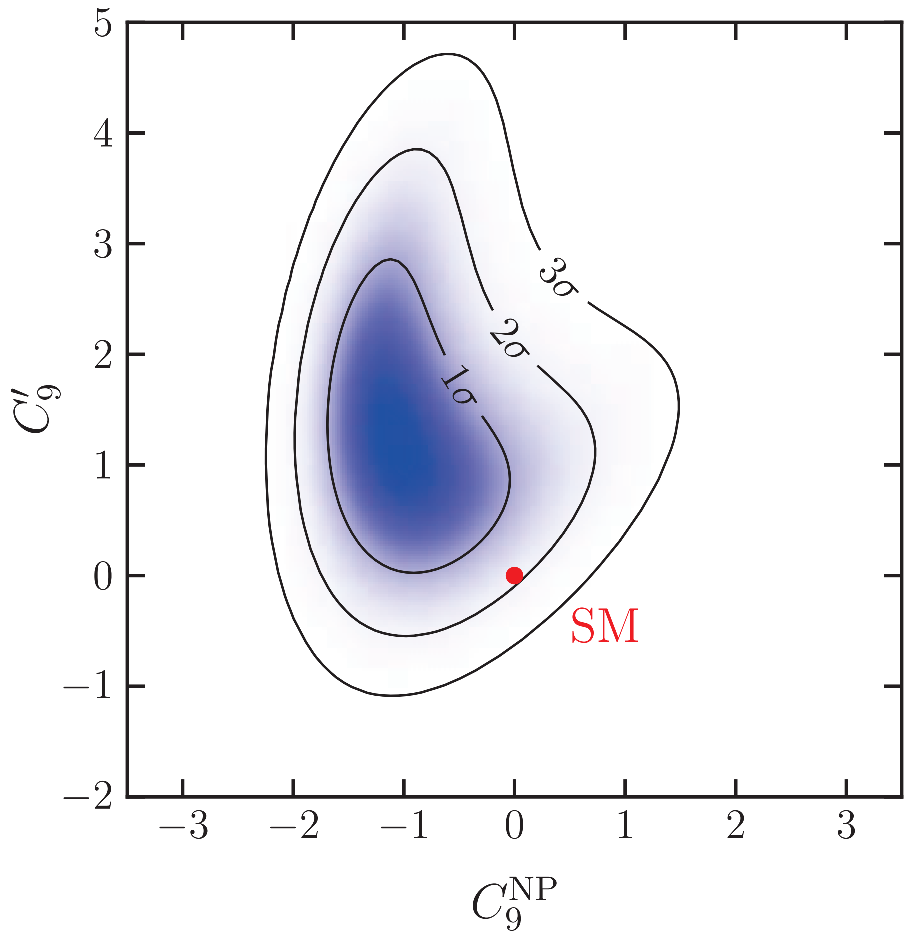
3. **Beaujean, Bobeth, van Dyck - 1310.2478**



Deviations: Fit of FCNC processes

Fits of penguins via $B_s \to \mu\mu$, $B \to K^{(*)} ll$, $b \to s\gamma$,...

4. **Horgan, Liu, Meinel, Wingate - 1310.3887**



Deviations: Charm

- D-mixing rate is large **(HFAG 2014)**

$$\frac{\Delta M}{\Gamma} = 0.39^{+0.16}_{-0.17}\% \qquad \frac{\Delta\Gamma}{2\Gamma} = 0.67^{+0.07}_{-0.08}\%$$

First single $> 5 = 9.3\sigma$ measurement by LHCb 1211.1230!

- Direct CP violation in hadronic Charm decays seen! (Naive SM: 10^{-4})

$$\Delta A_{CP}^{dir} = -0.253 \pm 0.104\%$$

LHCb; CDF; Belle

The crucial question: Can this be described within the SM or is it NP?

HQE seems to work well in the B-sector $\Rightarrow$ Try to apply it for Charm
Standard argument: the energy release is much too small, but

$$m_{B_s} - 2m_{D_s} \approx 1.43 \text{ GeV (momentum release: 3.5 GeV)}$$
$$m_D - 2m_K \approx 0.9 \text{ GeV (momentum release: 1.6 GeV)}$$
$$m_D - 2m_\pi \approx 1.6 \text{ GeV (momentum release: 1.8 GeV)}$$

Let's try!

Outline

- Motivation for Flavour Physics + State of the Art
  - Search for the Origin of Matter in the Universe
  - Identify New Physics (NP) Effects
  - Constrain Models for New Physics
- Highlights - What did we really learn so far?
  - The SM rules
  - Test of our theoretical Tools
  - Still Space for sizable New Physics Effects
  - Several interesting Deviations are still there
- Some Roads to follow
  - Higher Precision necessary
  - New Observables in the Search for New Physics
- Conclusion

Roads to follow - Summary

1. Huge $\#$ of flavour observables are **SM-like**
2. **Still some sizable space for NP effects**
3. **There are several interesting deviations in the present data**

Prepare for detecting smaller (i.e. not huge) deviations from the SM

1. Higher precision in theory and experiment - **NNLO-QCD, Lattice**
2. Challenge some text-book wisdom, e.g.
   - **Penguins are negligible**
   - **NP effects in tree-level decays are negligible**
3. Investigate quantities that are difficult to measure, e.g.:
   $B_q \to \tau\tau$, inclusive non-leptonic decays, $\Delta\Gamma_d$, ...
4. Look at the charm sector
5. Find NP in flavour observables

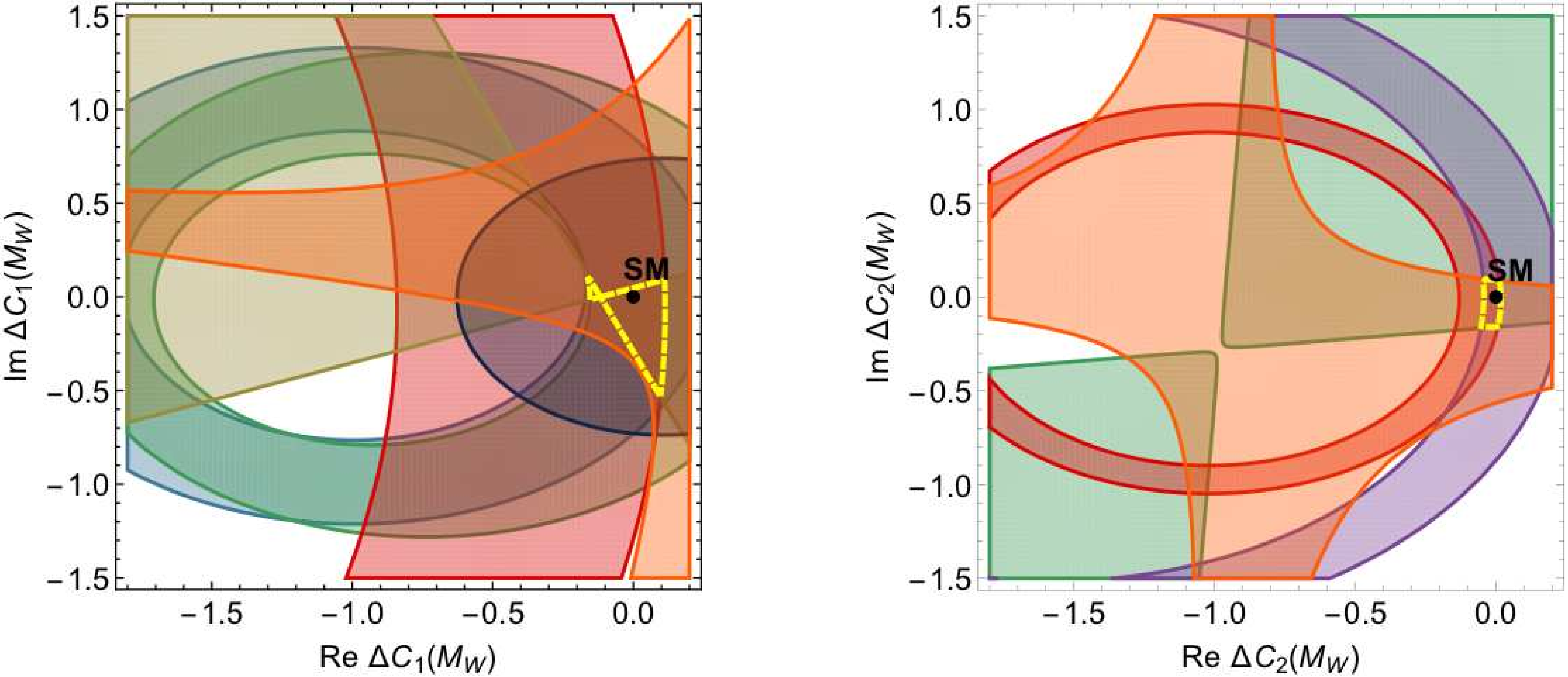
Roads to follow: NP in tree-level decays

- NP effects in penguins are quite well studied - many fits for C_7, C_9, C_{10},...
- *No NP effects in tree-level decays*, i.e. C_1 and C_2
  was a reasonable approximation some years ago,
  but should be challenged in view of the current experimental precision
- First systematic studies of NP effects in C_1 and C_2 in 2014:
  - Effects on $\Delta\Gamma_d$: **Bobeth, Haisch, AL, Pecjak, Tetlalmatzi-Xolocotzi, 1404.2531**
  - $B \to K\pi$-puzzle: **Bobeth, Gorbahn, Vickers, 1409.3252**
  - Effects on CKM-angle γ: **Brod, AL, Tetlalmatzi-Xolocotzi, Wiebusch, 1412.1446**
- Look at observables that
  - depend strongly on C_1 and C_2
  - can be reliably predicted
  - are precisely measured

  $\Rightarrow$ take bounds from
  $B \to D\pi$, $b \to s\gamma$, $b \to d\gamma$, lifetimes, $\sin\beta$, $B \to \pi\pi$, $\Delta\Gamma_s$ and $a_{sl}^{d,s}$

Roads to follow: NP in tree-level decays

Bounds on C_1 and C_2



Bobeth, Haisch, AL, Pecjak, Tetlalmatzi-Xolocotzi, 1404.2531

Is Im $\Delta C_1 = \pm 0.1$ large or small?

Roads to follow: NP in tree-level decays

Effects on the determination of the CKM angle γ

NP effects in C_1 and C_2 induce a shift $\delta\gamma$ in the determination of γ

$$\delta\gamma = (r_A - r_{A'}) \frac{\mathrm{Im}\Delta C_1}{C_2}$$

with the ratios of hadronic matrix elements (**different topologies!**)

$$r_{A'} = \frac{\langle \bar{D}^0 K^- | Q_1^{\bar{u}cs} | B^- \rangle}{\langle \bar{D}^0 K^- | Q_2^{\bar{u}cs} | B^- \rangle} \qquad r_A = \frac{\langle D^0 K^- | Q_1^{\bar{c}us} | B^- \rangle}{\langle D^0 K^- | Q_2^{\bar{c}us} | B^- \rangle}$$

with naive estimates for r_A and $r_{A'}$ we obtain

$$\mathrm{Im}\Delta C_1 = \pm 0.1 \Rightarrow \delta\gamma = \pm 4^\circ$$

This is huge!

Roads to follow: NP in tree-level decays

How to improve the bounds on C_1 and C_2?

- Include more observables
- NNLO-QCD to lifetimes and $\Delta\Gamma_s$
- smaller experimental error of $a_{sl}^{q,d}$
- Do a real fit - till now only scan
- Investigate more effects of NP in C_1 and C_2, e.g. $\Delta\Gamma_d$
- Identify NP models with effects in C_1 and C_2

How to improve the bounds on γ?

- Improved estimates on $r_A$and $r_{A'}$

Roads to follow: NP 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

Roads to follow: enhanced $b \to d, s\tau\tau$ transitions

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

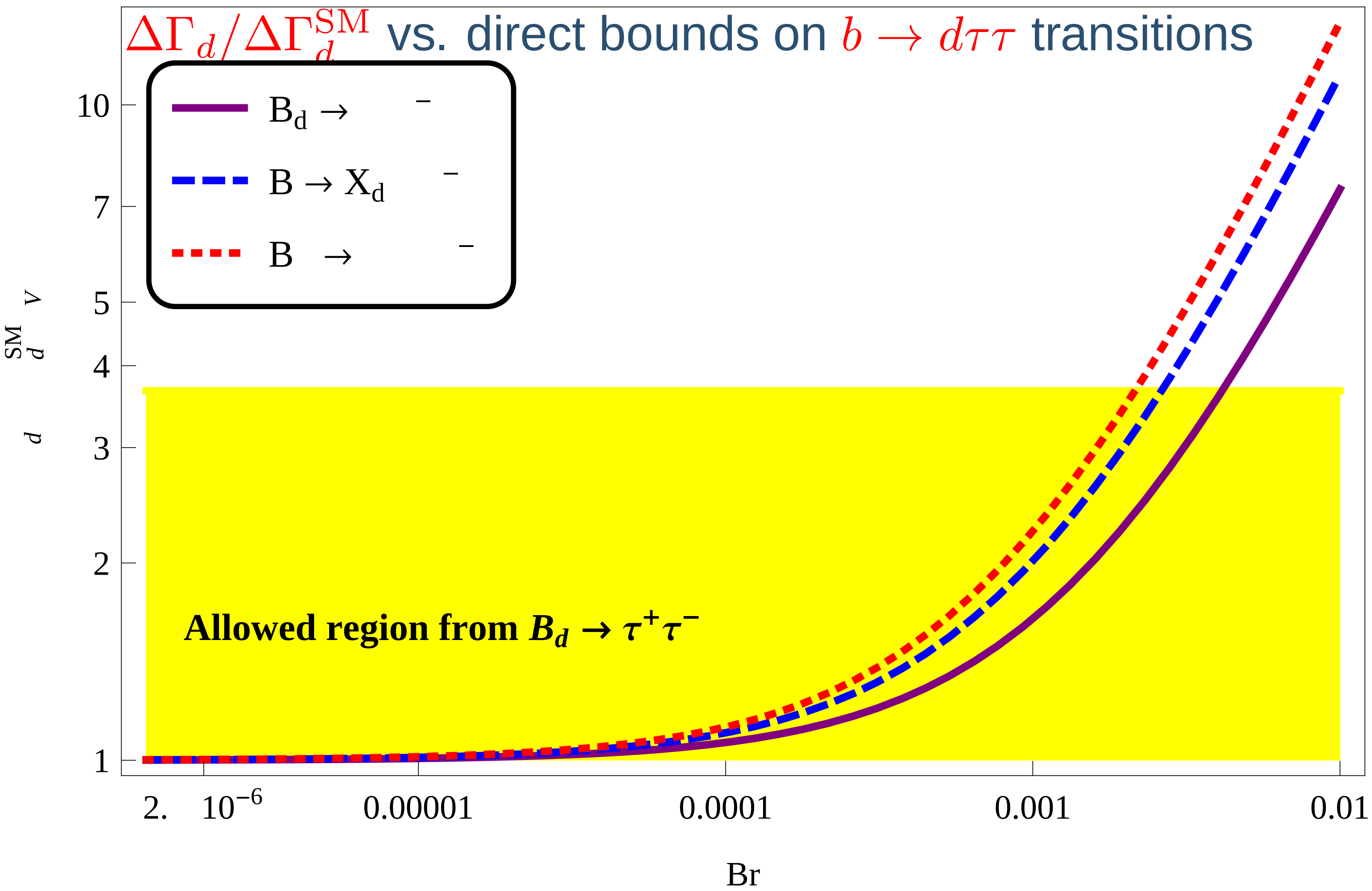
- $b \to d\tau\tau$ can enhance $\Delta\Gamma_d$ and a_{sl}^d. It is constrained by
  - $B_d \to \tau\tau < 4.1 \cdot 10^{-3}$ **direct** from **BaBar 2006**
  - $B \to X_d\tau\tau < 2.7\%$ **indirect from** $\tau(B_s)/\tau(B_d)$
  - $B^+ \to \pi^+\tau\tau < 2.7\%$ **indirect from** $\tau(B_s)/\tau(B_d)$

  $\Rightarrow$ 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

Roads to follow: enhanced $b \to d, s\tau\tau$ transitions

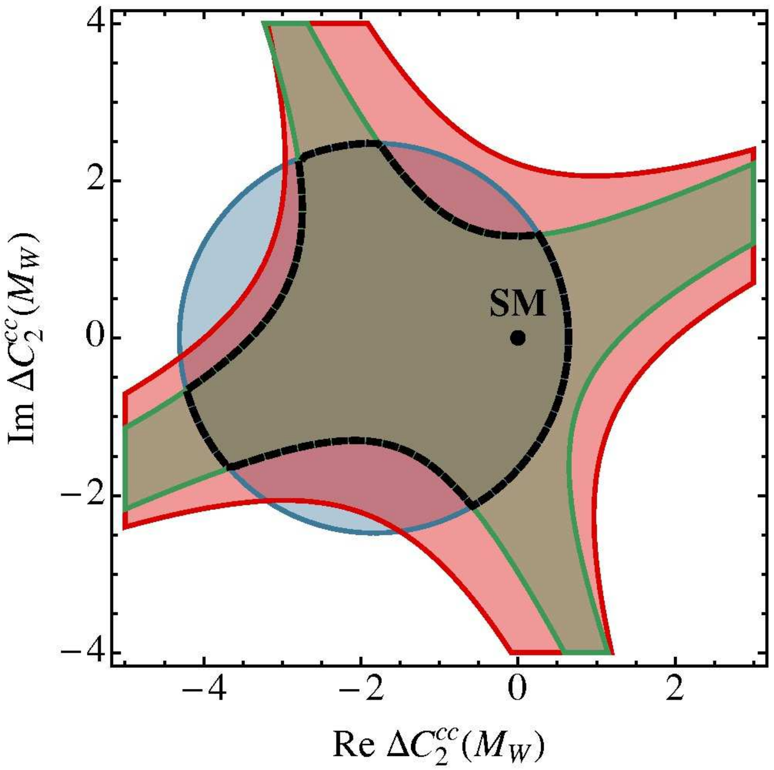


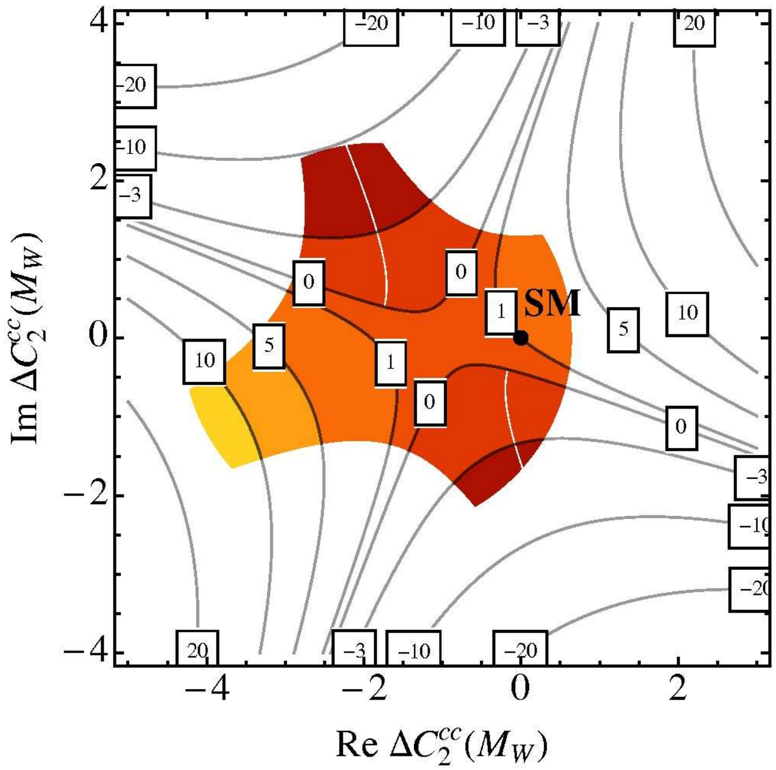
Bobeth, Haisch, AL, Pecjak, Tetlalmatzi-Xolocotzi, 2014

Roads to follow: NP 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**

Roads to follow: very New Physics

Test of the fundamentals of Quantum Mechanics with B-mixing

Bertlmann, Grimus 1997

Test decoherence in Quantum Mechanics

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

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, 2014

Roads to follow: Charm Observables

From a theory point the most "simple" quantities are the lifetimes

In the Charm-system huge lifetimes ratios appear, e.g.

$$\frac{\tau(D+)}{\tau(D^0)} = 2.536 \pm 0.019 \qquad \text{PDG 12}$$

Can theory cope with this?

Be aware:

- Λ / m_c might be too large ($\Lambda \neq \Lambda_{QCD}$!)
- $\alpha_s(m_c)$ might be too large

Roads to follow: Charm Observables

- '75-'78: Naive expectations (**before first data**):

$$\tau(D+)/\tau(D^0) \approx 1$$

- '79-'82: Naive expectations (**after first data hinting for a large difference**)

$$\tau(D+)/\tau(D^0) \approx 6...10$$

- Systematic HQE estimates **Voloshin, Shifman ('81,'85)**
  - LO-QCD, $1/N_c$: $\tau(D+)/\tau(D^0) \approx 2$ **Bigi, Uraltsev ('92-...)**
  - up-to-date estimate; NLO QCD **A.L., Rauh; 1305.3588**

$$\frac{\tau(D+)}{\tau(D^0)} = 2.2 \pm 1.7(0.4)(\text{hadronic ME})^{+0.3}_{-0.7}(\text{scale}) \pm 0.1(\text{parametric})$$

- Looks promising: huge lifetime difference might be explainable by the HQE
- **Hadronic matrix elements of the 4-quark operators urgently needed**

Dominant uncertainty: NNLO-QCD + Lattice

Conclusion

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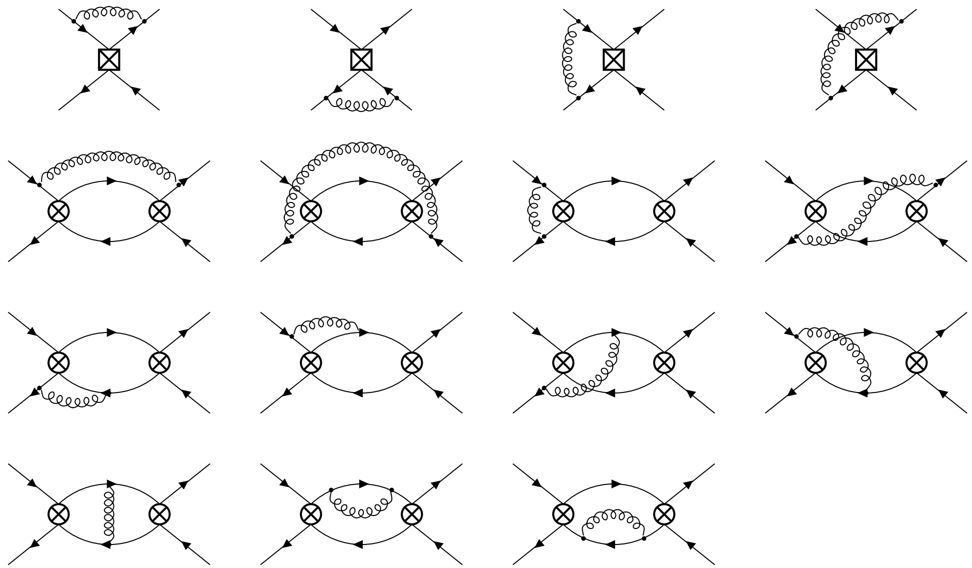
The SM rules VI: $\tau(B^+)/\tau(B_d)$ in NLO-QCD

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

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

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



A.L. 1405.3601

$$\left[\frac{\tau(B^+)}{\tau(B_d^0)}\right]_{NLO,HFAG\,14} = 1.04^{+0.05}_{-0.01} \pm 0.02 \pm 0.01 \leftrightarrow 1.076 \pm 0.004$$

The SM rules VII: $\tau(B^+)/\tau(B_d)$ in NLO-QCD

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

with non-perturbative input from **Becirevic hep-ph/0110124** - **13 years old!!!**

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

Huge Cancellations appear, see e.g. 1405.3601

$\Rightarrow$ extreme sensitivity on bag parameters!

Update urgently needed!

The SM rules VIII: $\tau(\Lambda_b)/\tau(B_d)$ - Experiment

Year	Exp	Decay	$\tau(\Lambda_b)$ [ps]	$\tau(\Lambda_b)/\tau(B_d)$
2014	HFAG	average	1.451 ± 0.013	0.955 ± 0.009
2014	LHCb	$J/\psi p K^-$	1.479 ± 0.013	0.974 ± 0.007
2013	CMS	$J/\psi \Lambda$	1.503 ± 0.061	$0.989 \pm 0.040*$
2012	ATLAS	$J/\psi \Lambda$	1.449 ± 0.040	$0.954 \pm 0.026*$
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	$0.74 \pm 0.24*$

The SM rules IX: $\tau(\Lambda_b)/\tau(B_d)$ - Theory

Year	Author	$\tau(\Lambda_b)/\tau(B_d)$
2014	A.L. **1405.3601**	0.935 ± 0.054
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

The SM rules X: $\tau(\Lambda_b)/\tau(B_d)$ at Order $1/m_b^2$

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

Leading Term

$$
\begin{aligned}
\frac{\Lambda^2}{m_b^2}\Gamma_2 \quad & = \quad \frac{\mu_\pi^2(\Lambda_b) - \mu_\pi^2(B_d)}{2m_b^2} + \frac{c_G}{c_3}\frac{\mu_G^2(B_d) - \mu_G^2(\Lambda_b)}{2m_b^2} \\
& = \quad \frac{(0.1 \pm 0.1)\,\text{GeV}^2}{2m_b^2} - 1.1\,\frac{0.35\,\text{GeV}^2 - 0}{2m_b^2} \\
& \approx \quad (0.003 \pm 0.003) - (0.011 \pm 0.003) = -0.008 \pm 0.005
\end{aligned}
$$

A.L. 1405.3601 with inputs from **Bigi, Mannel, Uraltsev**, 2011

The SM rules XI: $\tau(\Lambda_b)/\tau(B_d)$ at Order $1/m_b^3$

$$
\begin{aligned}
\frac{\tau(\Lambda_b)}{\tau(B_d)} = 1 \quad & - \quad 0.008 \\
& + \quad \frac{\Lambda^3}{m_b^3}\left(\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{(1)} + \ldots\right) \\
& + \quad \frac{\Lambda^4}{m_b^4}\left(\Gamma_4^{(0)} + \ldots\right) + \frac{\Lambda^5}{m_b^5}\left(\Gamma_5^{(0)} + \ldots\right) + \ldots
\end{aligned}
$$

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

- Wilson coefficient of $\Gamma_3^{(0)}$, e.g. 1996 **Uraltsev/ Neubert and Sachrajda**
  Part of $\Gamma_3^{(1)}$ 2002 **Franco, Lubicz, Mescia, Tarantino**
- **Non-perturbative** matrix elements of 4-quark operators
  HQET: only two different matrix elements (instead of four)

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

The SM rules XII: $\tau(\Lambda_b)/\tau(B_d)$ Matrix Elements

Values for r:

$r \approx 0.2$	*Bag model*	**Guberina, Nussinov, 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*	**–”–**

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

The SM rules XIII: $\tau(\Lambda_b)/\tau(B_d)$ Matrix Elements

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 2014**: $\tau_{\Lambda_b}/\tau_{B_d} = 0.935 \pm 0.054$ **AL 1405.3601**

$$\Rightarrow r = 0.62 \pm 0.06$$

The SM rules XIV: $\tau(\Lambda_b)/\tau(B_d)$: Matrix Elements

1999 **DiPierro, Sachrajda, Michael**:

currently the only lattice determination!

- **15 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 and by accident fitted the low experimental number of that time...

The SM rules XV: clean Ratio $\tau(\Xi_b^0)/\tau(\Xi_b^+)$

- Disconnected contributions cancel in $\tau(\Xi_b^0)/\tau(\Xi_b^+)$ as in $\tau(B^+)/\tau(B_d)$
- No matrix elements for Ξ_b available - assume they are equal to the Λ_b
  $\Rightarrow$ $???$: unknown systematic hadronic errors
- Get rid of unwanted $s \to u$-transitions $\bar{\Gamma}(\Xi_b) = \Gamma(\Xi_b) - \Gamma(\Xi_b \to \Lambda_b + X)$.

$$\frac{\bar{\tau}(\Xi_b^0)}{\bar{\tau}(\Xi_b^+)} = 0.94 \pm 0.04 \pm ??? \qquad \frac{\tau(\Xi_b^0)}{\tau(\Xi_b^-)} = 0.924 \pm 0.035$$

$$\bar{\tau}(\Xi_b^0) = \tau(\Lambda_b) \qquad \frac{\tau(\Xi_b^0)}{\tau(\Lambda_b)} = 1.006 \pm 0.018 \pm 0.010$$

$$\frac{\tau(\Lambda_b)}{\bar{\tau}(\Xi_b^+)} = 0.95 \pm 0.06 \pm ??? \qquad \frac{\tau(\Lambda_b)}{\tau(\Xi_b^-)} = 0.918 \pm 0.026 \pm 0.011$$

Theory: **AL 1405.3601** based on
Beneke, Buchalla, Greub, AL, Nierste 2002

Exp.: **LHCb 1405.7223, 1409.8568**

The SM rules XVI: $\tau(B_s)$

- $\tau(B_s)/\tau(B_d)$: Almost perfect cancellation of all spectator quark contributions in the HQE

HFAG 2014 vs. **AL 1405.3601**

$$\frac{\tau(B_s)}{\tau(B_d)}^{\text{Exp}} = 0.995 \pm 0.006 \qquad \frac{\tau(B_s)}{\tau(B_d)}^{\text{SM}} = 1.001 \pm 0.002$$

- Gives model independent bounds on invisible NP contributions
- $\Phi_s, \Delta\Gamma_s$ can also be extracted 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**

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

see also Dunietz, Fleischer, Nierste PRD63 (2001) 114015, hep-ph/0012219

The SM rules XVII: Effective 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

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

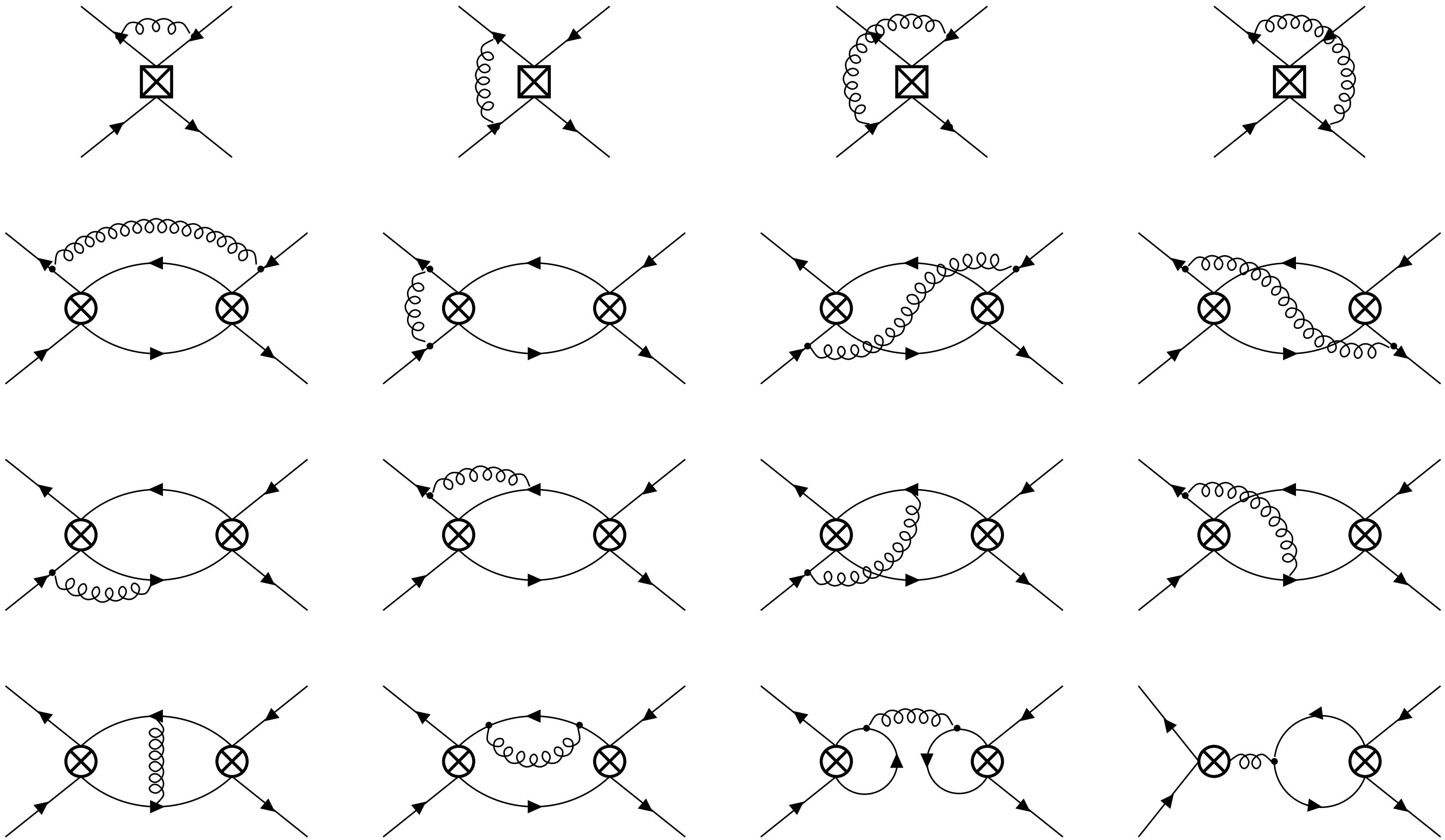
The SM rules XVIII: further Lifetimes

- $\tau(B_c)$: three contributions
  1. c-quark decays
  2. b-quark decays
  3. $b - c$-annihilation

$$\tau(B_c) = 0.500 \pm 0.013\,\text{ps} \quad \textbf{HFAG 2014}$$
$$\tau(B_c)_{\rm LO} = 0.52^{+0.18}_{-0.12}\,\text{ps} \quad \textbf{Beneke, Buchalla 1996}$$

Roads to follow I - Higher Precision in Γ_{12}

Calculating the following diagrams



Roads to follow II - Higher Precision in Γ_{12}

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!

Roads to follow III - Higher Precision in Γ_{12}

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

Roads to follow IV - Higher Precision in Γ_{12}

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%

Roads to follow V - How large are penguins?

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

$$S_{\psi\phi}^{\rm SM} = 0.0036 \pm 0.0012 \to \sin\left(2\beta_s - \phi_s^{\Delta} - \delta_s^{\rm Peng,SM} - \delta_s^{\rm Peng,NP}\right) = 0.00 \pm 0.07$$

HFAG 2014

Is this a contraction to the dimuon asymmetry?

Depends on the possible size of penguin contributions

- SM penguins are expected to be very small
  e.g $\leq 1\%$ for $B_d \to J/\psi K_s$ **Jung 1206.2050**
  but see also **Faller, Fleischer; Mannel 2008**
- NP penguins might be larger
- Experimental cross-check! e.g. $B_s \to \phi\phi$ **LHCb Moriond 2013**

But: even small penguin contributions have a sizable effect! **A.L. 1106.3200**

Roads to follow VI - How large are penguins?

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)

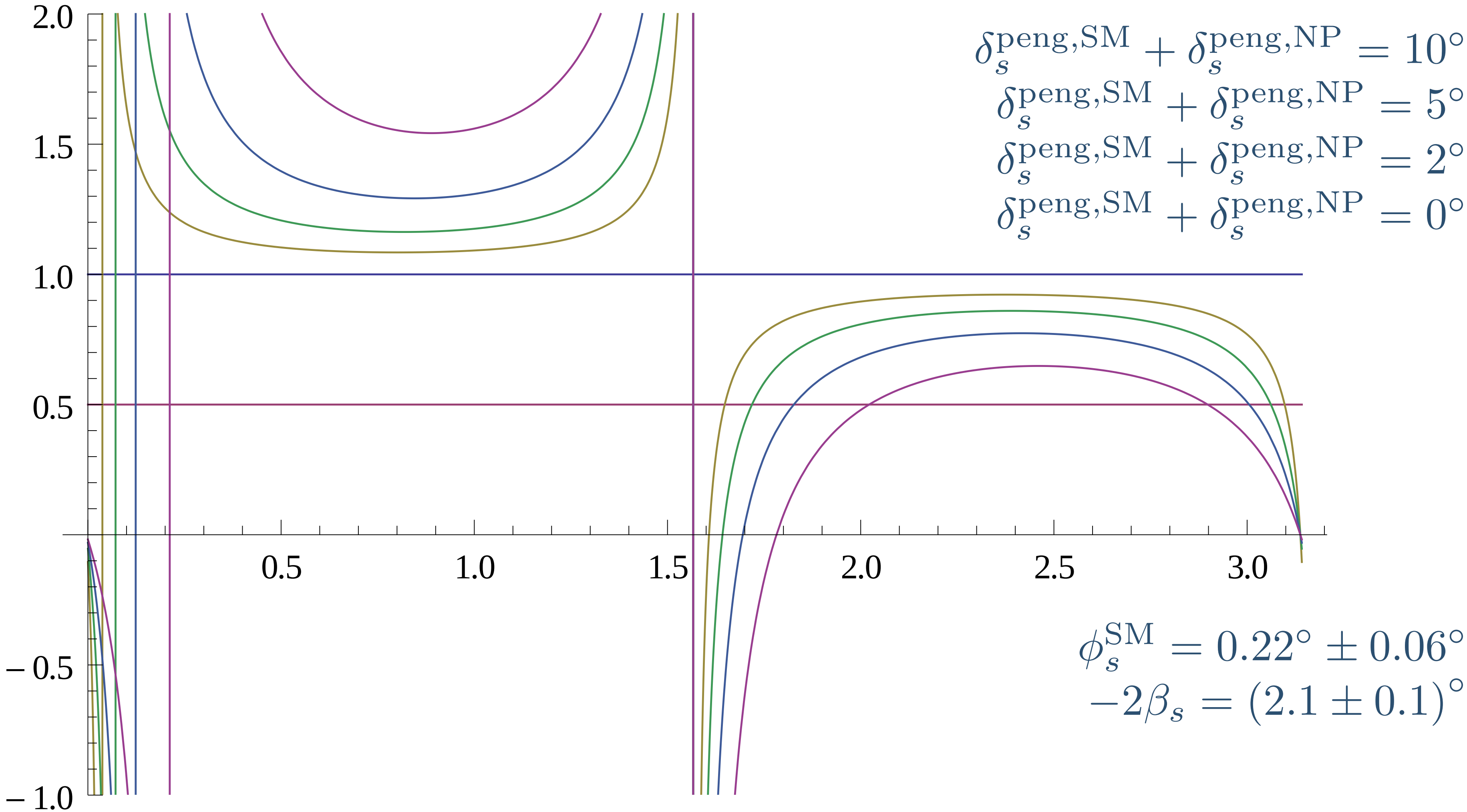
$$a_{sl}^s = -\frac{\Delta\Gamma}{\Delta M}\frac{S_{\psi\phi}}{\sqrt{1-S_{\psi\phi^2}}}\cdot\delta$$

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

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

A.L. 1106.3200

Roads to follow VII - How large are penguins?



- 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