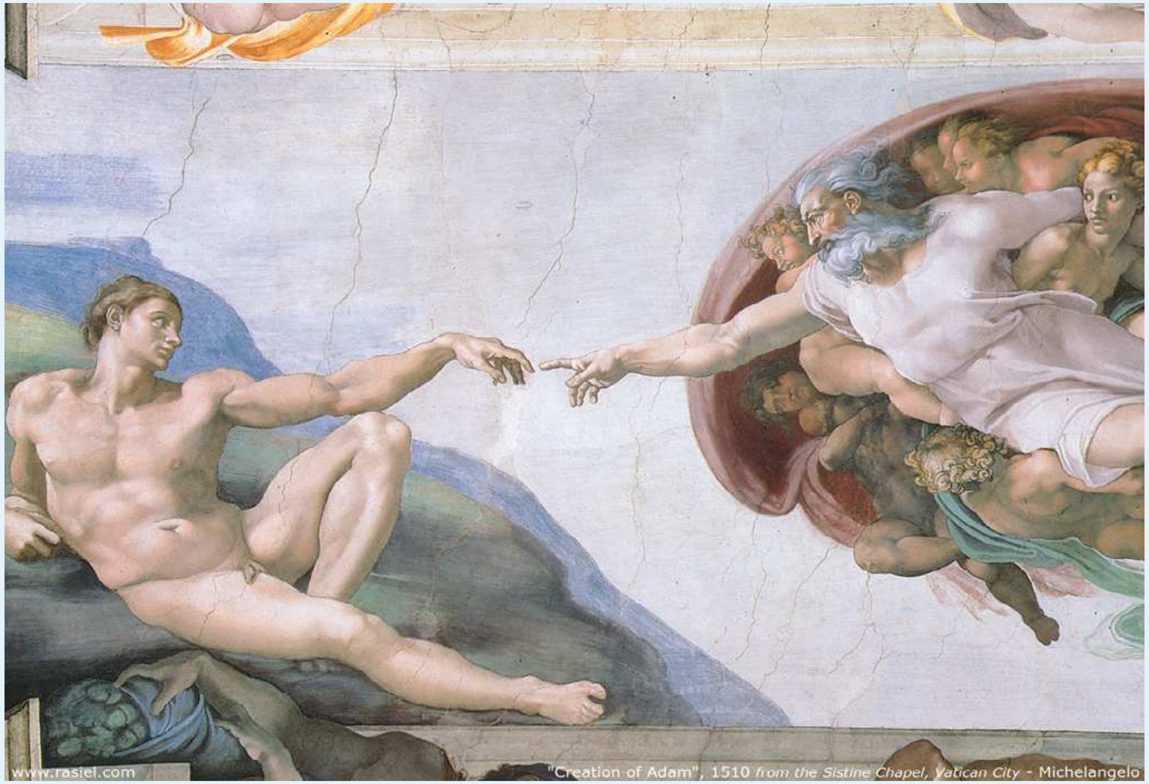
The status of Flavour Physics in 2013



Alexander Lenz

IPPP Durham

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?
  - Test of our theoretical Understanding
  - Search for New Physics
  - The second Charm Revolution
- Some Roads to follow
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  - Search for New Physics
  - Explore the Charm Sector
- Conclusion

A new Clue to explain Existence

- 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
- ...

A new Clue to explain Existence

- 1005.2757 D0 (submitted Sunday, 16.5.2010) 246 citations

PHYSICAL REVIEW D **82,** 032001 (2010)

Evidence for an anomalous like-sign dimuon charge asymmetry

V. M. Abazov,[36] B. Abbott,[74] M. Abolins,[63] B. S. Acharya,[29] M. Adams,[49] T. Adams,[47] E. Aguilo,[6] G. D. Alexeev,[36]

We measure the charge asymmetry A of like-sign dimuon events in 6.1 fb^{-1} of $p\bar{p}$ collisions recorded with the D0 detector at a center-of-mass energy $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron collider. From A, we extract the like-sign dimuon charge asymmetry in semileptonic b-hadron decays: $A^b_{\rm sl} = -0.00957 \pm 0.00251\,({\rm stat}) \pm 0.00146\,({\rm syst})$. This result differs by 3.2 standard deviations from the standard model prediction $A^b_{\rm sl}({\rm SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$ and provides first evidence of anomalous CP violation in the mixing of neutral B mesons.

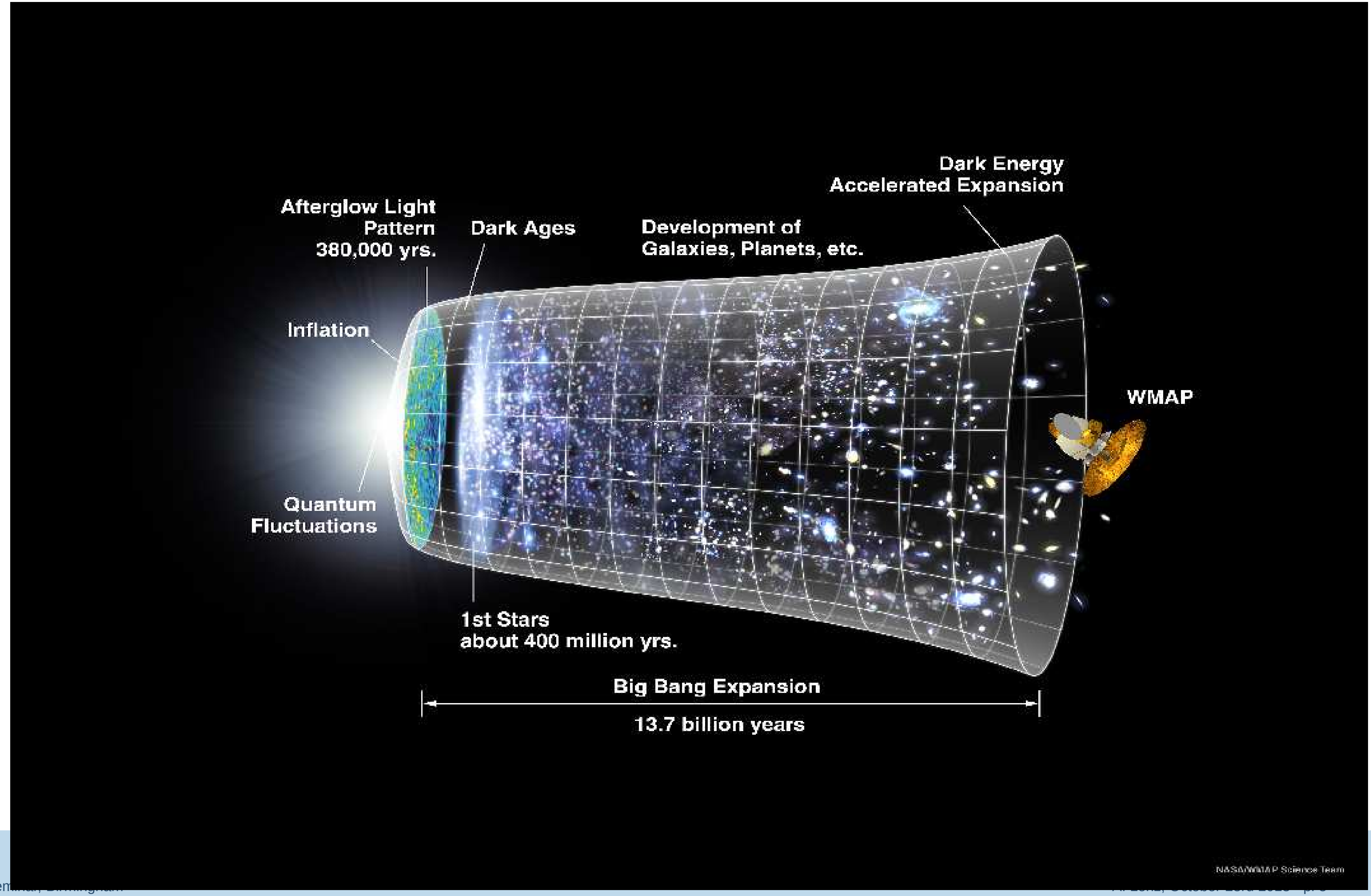
DOI: 10.1103/PhysRevD.82.032001 PACS numbers: 13.25.Hw, 11.30.Er, 14.40.Nd

[1] A. Lenz and U. Nierste, J. High Energy Phys. 06 (2007) 072.
[2] C. Amsler *et al.*, Phys. Lett. B **667**, 1 (2008), and 2009 partial update for the 2010 edition.
[15] V. M. Abazov *et al.* (D0 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **565**, 463 (2006).
[16] S. N. Ahmed *et al.*, arXiv:1005.0801 [Nucl. Instrum. Methods Phys. Res. Sect. A (to be published)]; R.

17.5.'10 NYT: "A new clue to explain existence" ($69 \cdot 10^6$ Google entries)

- 1106.6308: 9 fb^{-1}, $A^b_{sl} = (-0.787 \pm 0.172(stat) \pm 0.093(syst))\% \Rightarrow 3.9\sigma$

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, nucleosynthesis, CMB,...

Motivation - Baryon Asymmetry

Search for annihilation lines, nucleosynthesis, CMB,...

Motivation - Baryon Asymmetry

Search for annihilation lines, nucleosynthesis, 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?

Motivation - Baryon Asymmetry

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

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

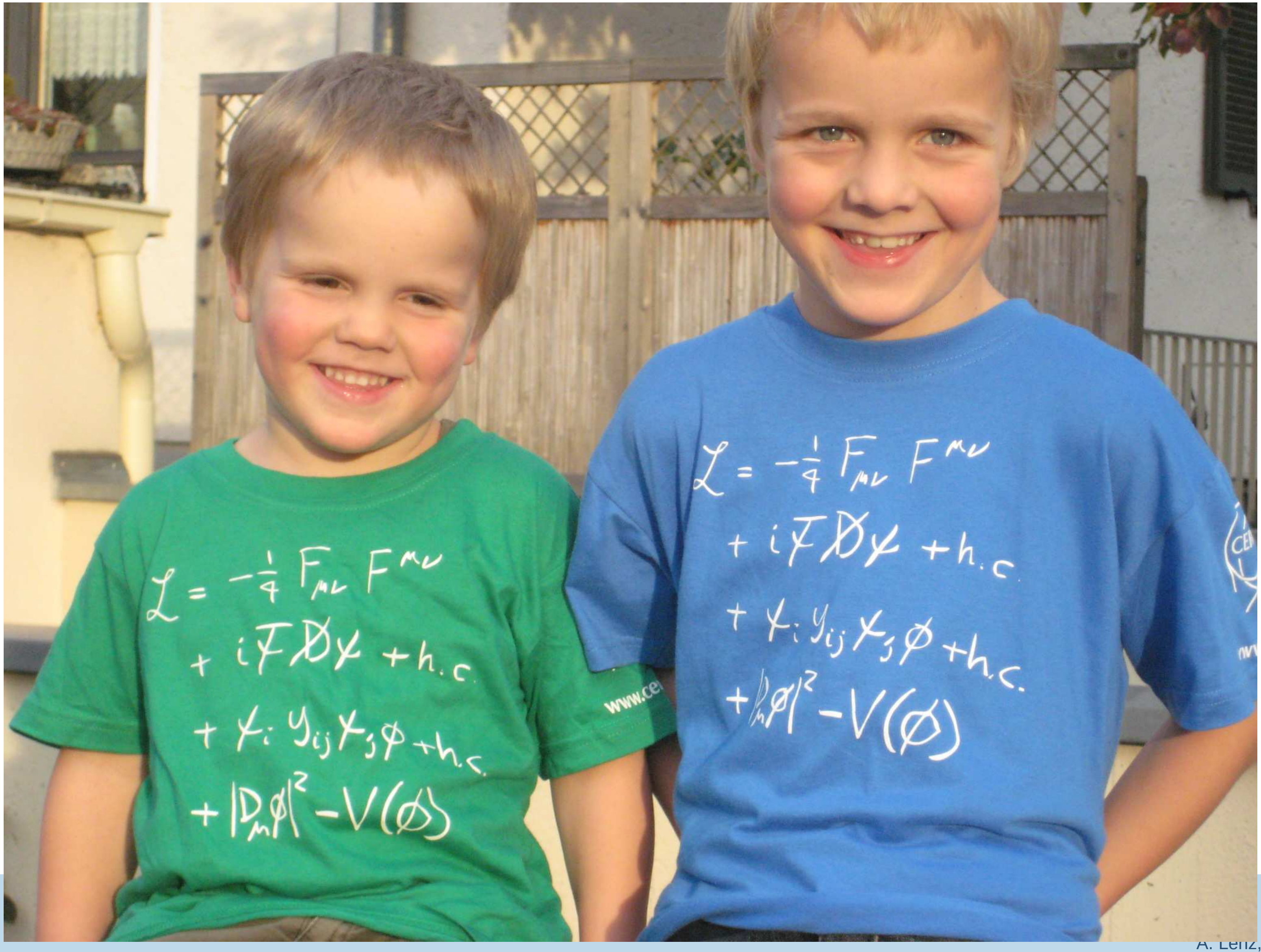
How can this be created from symmetric initial conditions?

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

CP-violation: 1964 Kaons (NP ’80); 2000 B_d; 2011 Charm?; 2012 B^+;2013 B_s

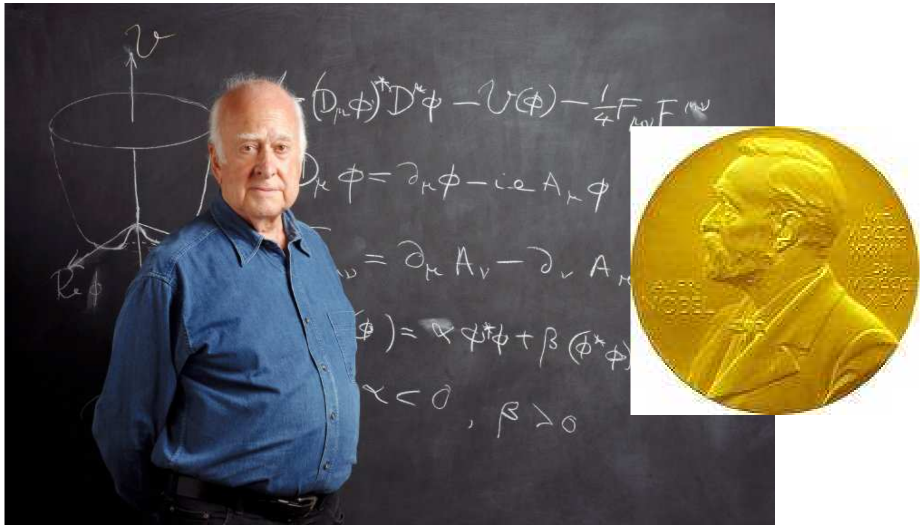
Can our fundamental theory cope with these requirements?

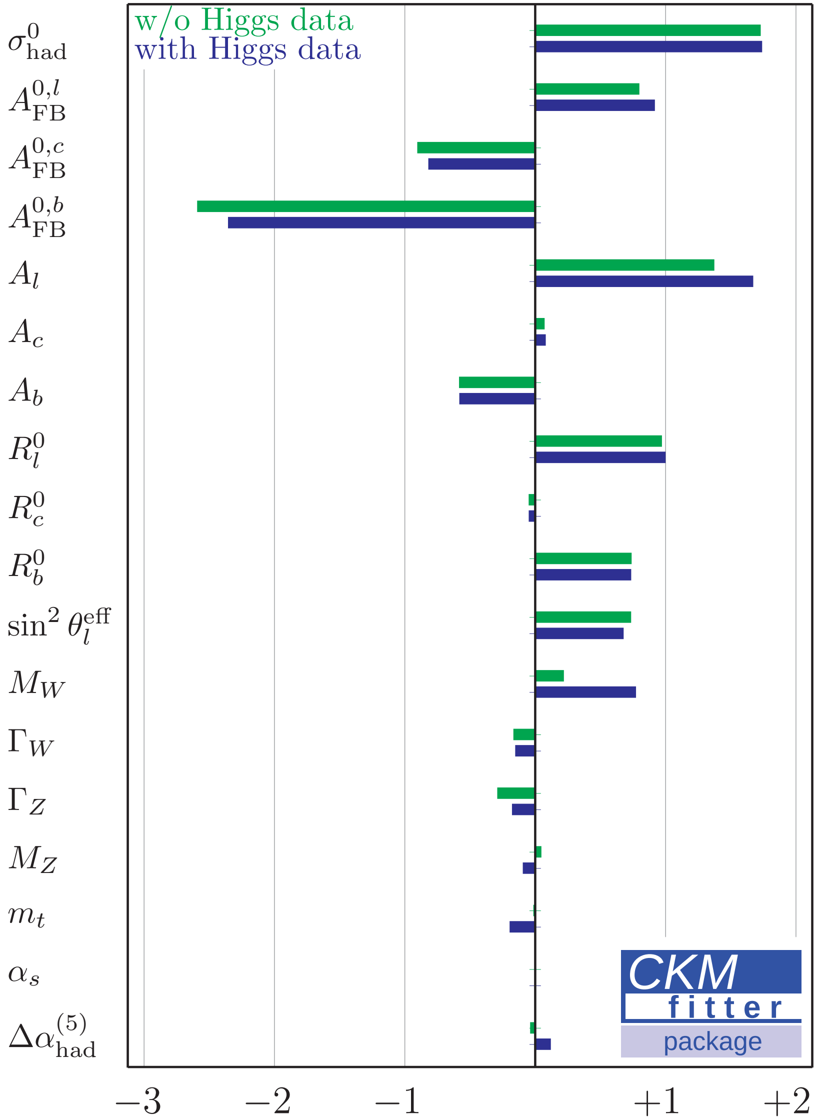
The Standard Model = elegant description of nature at per mille precision



Motivation - Our fundamental Theory

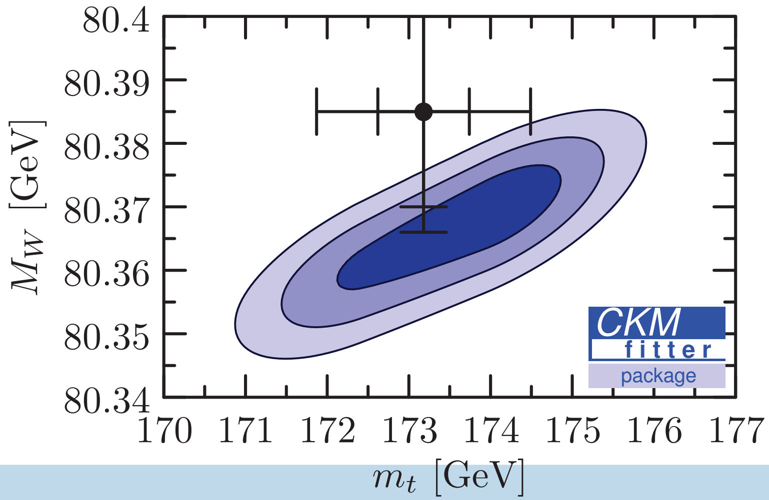
SM seems to be complete now - first electro-weak fit





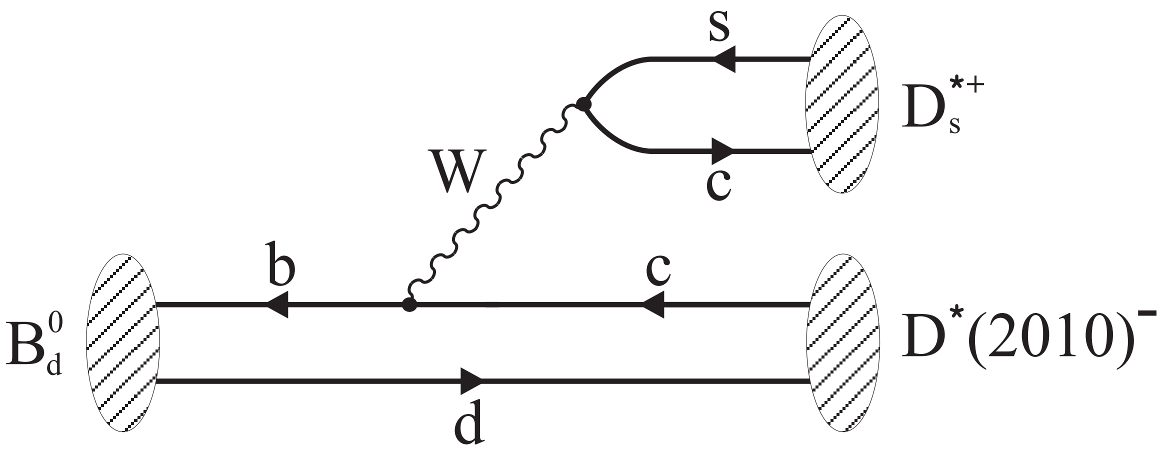
Eberhardt et al = A.L., KIT, HU Berlin 1209.1101

see also **GFitter 1209.2716**



Motivation - Our fundamental Theory

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**

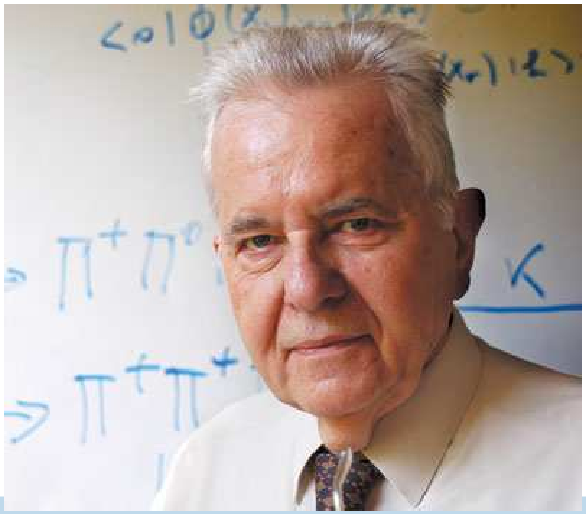
Motivation - Our fundamental Theory

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!

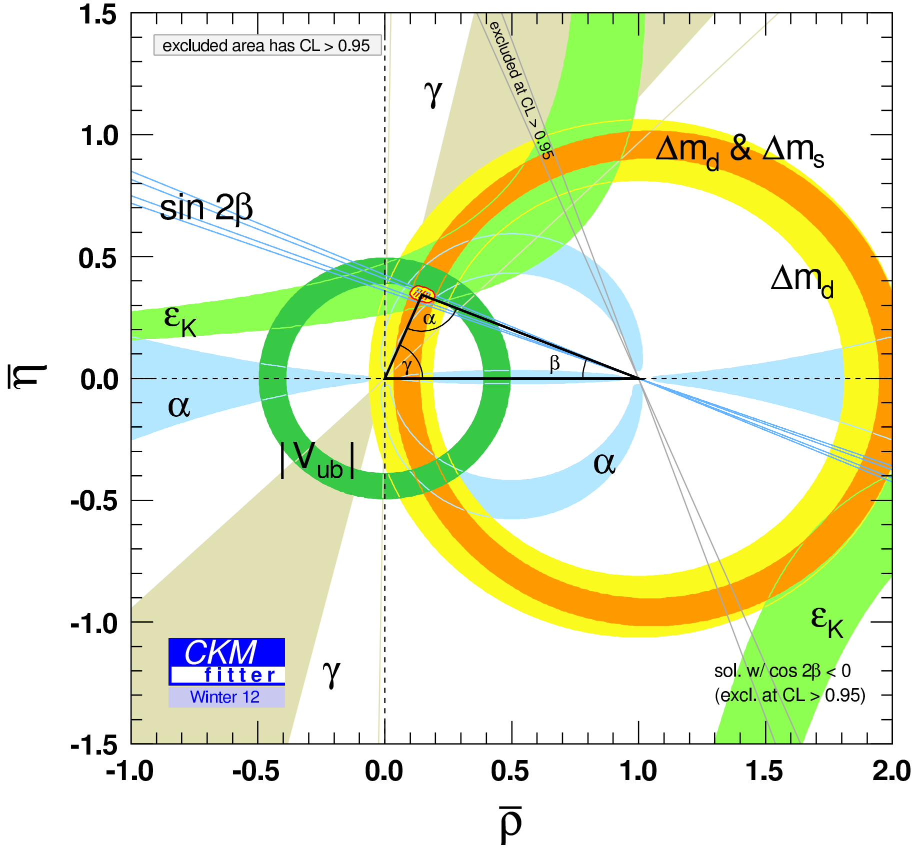
$$|V_{CKM}| = \begin{pmatrix} 0.974452^{+0.000033}_{-0.000432} & 0.22457^{+0.00186}_{-0.00014} & 0.00355^{+0.00016}_{-0.00013} \\ 0.22443^{+0.00186}_{-0.00015} & 0.973607^{+0.000069}_{-0.000445} & 0.04151^{+0.00056}_{-0.00115} \\ 0.00875^{+0.00016}_{-0.00031} & 0.04073^{+0.00055}_{-0.00113} & 0.999132^{+0.000047}_{-0.000024} \end{pmatrix}$$

Fit from **CKMfitter 2013**, 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?

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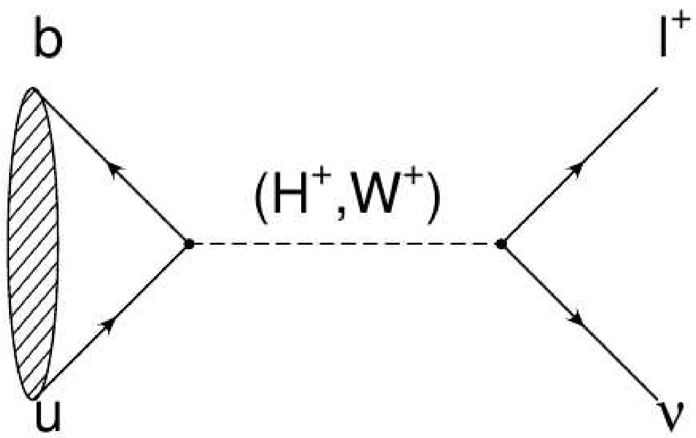
Indirect Search for New Physics

Strategy: Look at mesons decays

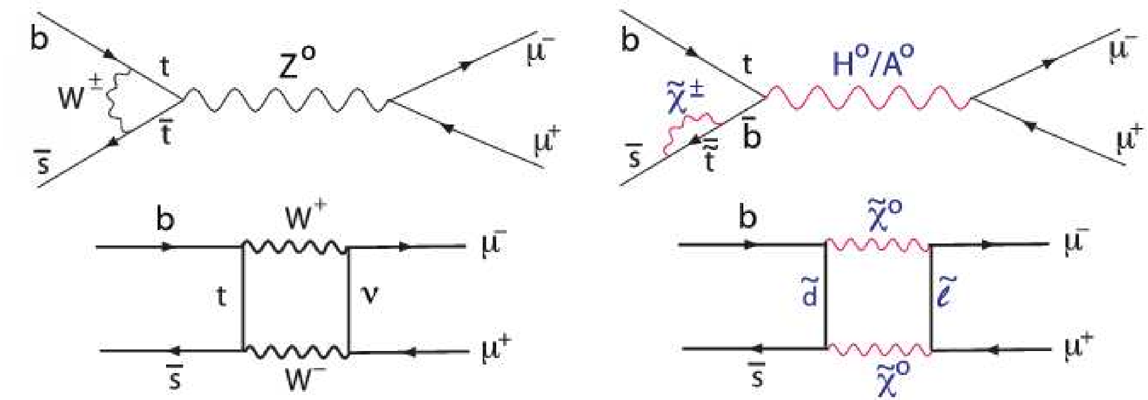
1. Calculate the decays very precisely in the SM
2. Find a deviation in experiment

Examples:

- $B \to \tau \nu$



- $B_s \to \mu\mu$



Status before LHC: V_{ub}-problem

Exclusive	$\lvert V_{ub}\rvert = 0.00351 \pm 0.00047$
Inclusive	$\lvert V_{ub}\rvert = 0.00432 \pm 0.00027$
$B \to \tau\nu$	$\lvert V_{ub}\rvert = 0.00504 \pm 0.00064$
Fit	$\lvert V_{ub}\rvert = 0.00355 \pm 0.00015$

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,...

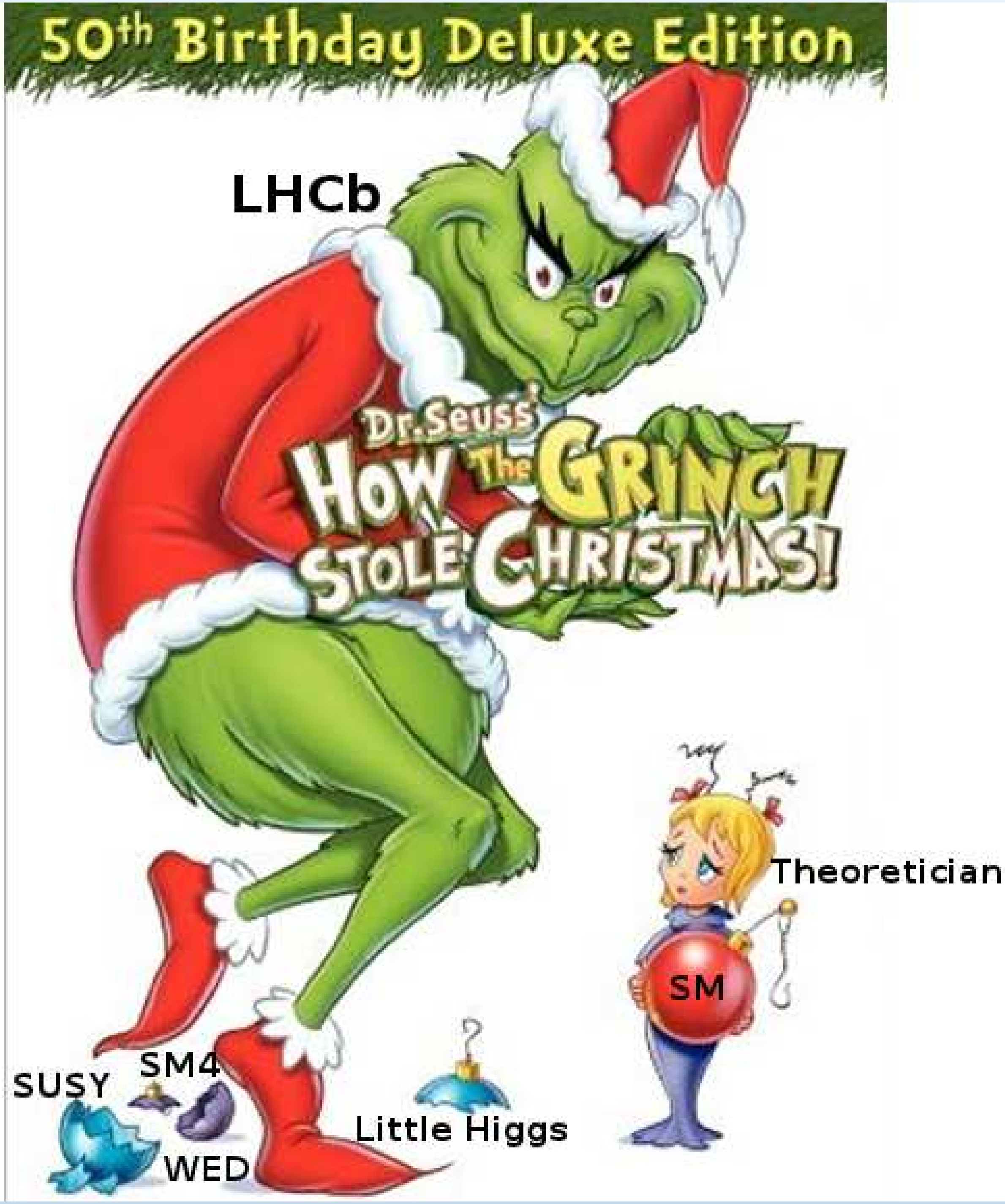
- V_{ub} is actually of order λ^4 and not λ^3: $0.00355 = (0.22457)^{3.77673}$
- Hadronic uncertainties (lattice, LCSR) underestimated?
- **Soni and Lunghi:** do not to use V_{ub} in the global fit
- **Crivellin0907.2461; Buras/Gemmler/Isidori 1007.1993:** RH currents $\Rightarrow$ *incl.* $\neq$ *excl.*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

Flavour Physics: Status before LHC

- Overall consistency of the CKM picture is very good
  - Mechanism awarded with the Nobel Prize
  - Also agreement on loop-level e.g. rare processes like $b \to s\gamma$
  - Still higher precision necessary, e.g. V_{td} and V_{ts} almost unconstrained
    Current constraints still allow $V_{u'b} > V_{ub}$ and $V_{c'b} > V_{cb}$

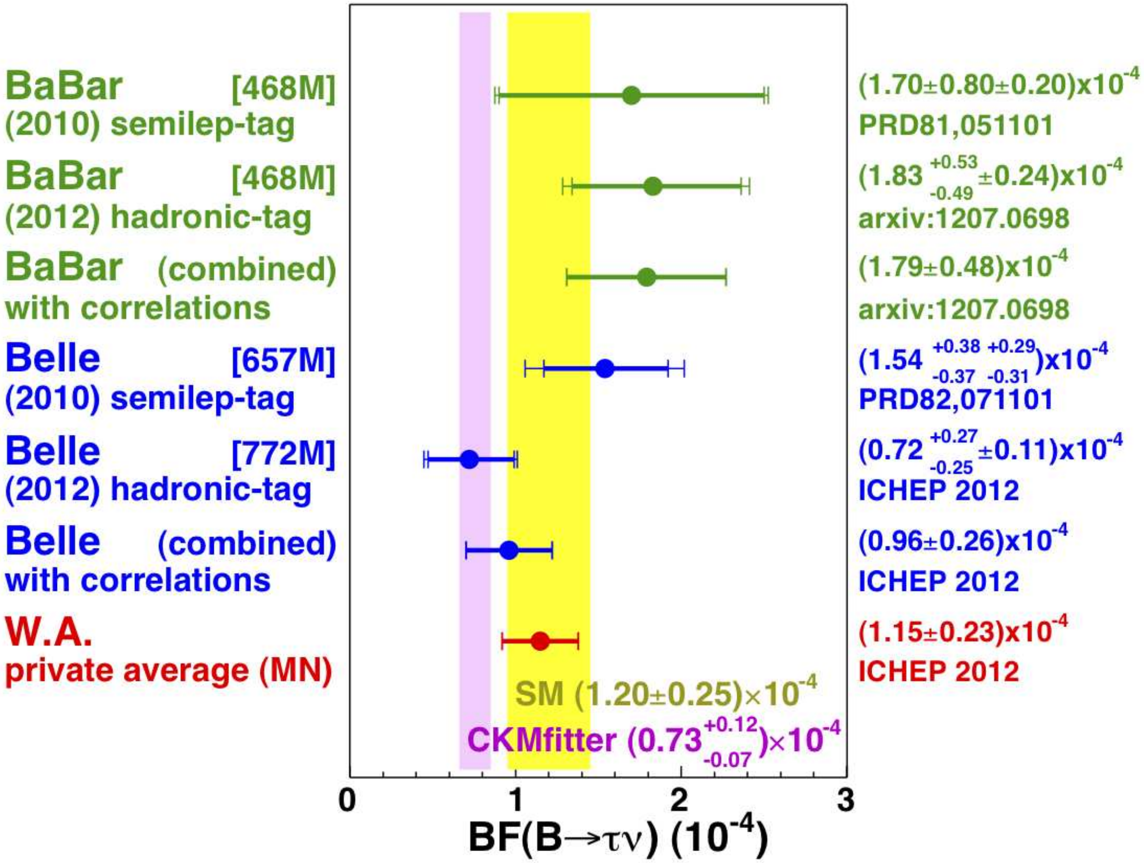
- Several interesting deviations from the CKM picture have arisen
  - Evidence for huge new physics phase in B-mixing:
    dimuon asymmetry; $B_s \to J/\psi\phi$...
  - CDF has hints for a very large $B_s \to \mu\mu$ branching ratio
  - Problems with $\sin 2\beta$ - V_{ub} - $B \to \tau\nu$

Status in 10/13: We expected a lot, and then...



Status in 10/13: $B \to \tau\nu$

Also 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 1205.5442** or also hadronic uncertainties **Becirevic et al 1206.4977**

Status in 10/13: $B_s \to \mu\mu$

CDF **1301.7048** was not confirmed by
ATLAS **1204.0735**, D0 **1301.4507**, CMS **1307.5025** and **LHCb** **1307.5024**

$$Br(B_s \to \mu\mu) = 2.9^{+1.1}_{-1.0} \cdot 10^{-9} \qquad (\text{LHCb}, 4.0\sigma, 3fb^{-1})$$
$$Br(B_s \to \mu\mu) = 3.0^{+1.0}_{-0.9} \cdot 10^{-9} \qquad (\text{CMS}, 4.3\sigma, 25fb^{-1})$$

This agrees perfectly with the SM expectation

$$Br(B_s \to \mu\mu) = 3.64^{+0.21}_{-0.32} \cdot 10^{-9}$$ **CKMfitter**

$$Br(B_s \to \mu\mu) = 3.23 \pm 0.27 \cdot 10^{-9}$$ **Buras et al 1208.0934**

This numbers have to be corrected due to

- Finite $\Delta\Gamma_s$: about $+10\%$ — **Fleischer et al. 1204.1735; 1204.1737**
- Soft Photons: about: -10% — **Petrov in April at CERN, 1212.4166; Buras et al 1208.0934**

Status in 10/13: Disappearing Discrepancies

- **SM and theoretical tools work even better**
  - Many discrepancies disappeared $B \to \tau\nu$, $B_s \to \mu\mu$, ...:

Does this kill models?

Absence of evidence is not evidence of absence

Not true for the SM4, but true for decoupling theories, like SUSY

SUSY is not dead yet, but it is not showing any sign of life

Rules out part of previously interesting SUSY parameter space

- But some discrepancies remain, e.g.
  - V_{ub}
  - A_{sl}^b
  - $B \to D^{(*)}\tau\nu$
  - $B \to K^*\mu\mu$
  - ...
- Some very interesting results in the Charm sector

Constraining Models of NP

How to really kill a model of NP

The SM4 (perturbative, chiral fourth generation of fermions) was killed many times, but always under unjustified assumptions

Kribs, Plehn, Tait, Spannowsky '07 (358 cit.)

Novikov, Okun, Rozanov, Vysotsky '00, '02,...(113 cit.)

- Flavour effects **A.L. et al '09**
- Electro-weak + CKM mixing **A.L. et al '10**

The final death:

- in principle: **Djouadi, A.L. '12**
- in practice: **A.L., KIT, HU Berlin '12**

Combined fits of Flavour, Higgs, electro-weak observables are crucial!

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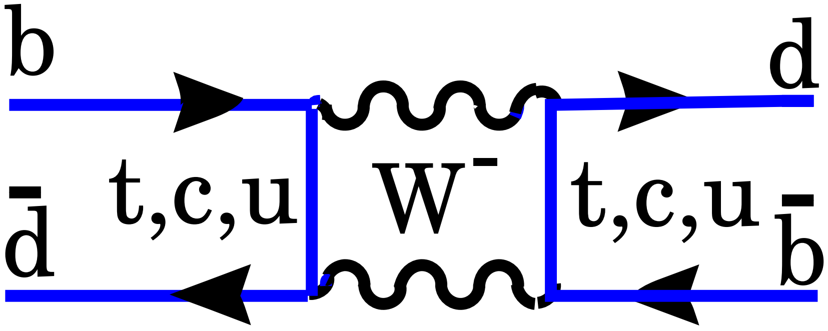
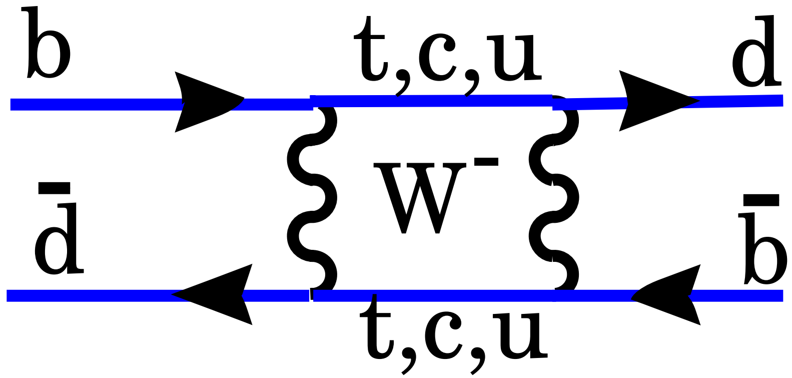
Test of our theoretical Understanding





$|M_{12}|$, $|\Gamma_{12}|$ 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. $B_q \to X l \nu$ (*semi-leptonic*)

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

Test of our theoretical Understanding

- **Mass difference:** One Operator Product Expansion (OPE)

  Theory **A.L., Nierste 1102.4274** vs. Experiment : **HFAG 13**

$$\Delta M_d = 0.543 \pm 0.091 \text{ ps}^{-1} \qquad \Delta M_d = 0.510 \pm 0.004 \text{ ps}^{-1}$$
$$\Delta M_s = 17.30 \pm 2.6 \text{ ps}^{-1} \qquad \Delta M_s = 17.69 \pm 0.08 \text{ ps}^{-1}$$

  - Perfect agreement, still room for NP
  - Important bounds on the unitarity triangle and NP
  - **Dominant uncertainty = Lattice**

- **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 Understanding

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 $n_c^{\text{Exp.}} < n_c^{\text{SM}}$, 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 Understanding

(Almost) all discrepancies disappeared:

- '12: $n_c^{2011\mathrm{PDG}} = 1.20 \pm 0.06$ vs. $n_c^{\mathrm{SM}} = 1.23 \pm 0.08$ **Krinner, A.L., Rauh 1305.5390**
- HFAG '03 $\tau_{\Lambda_b} = 1.229 \pm 0.080$ ps^{-1} $\longrightarrow$ HFAG '13 $\tau_{\Lambda_b} = 1.429 \pm 0.024$ ps^{-1}
  Shift by 2.5σ!; (ATLAS: 1.45 ± 0.04 ps/CMS: 1.50 ± 0.06 ps/LHCb: 1.482 ± 0.022 ps)
- **HFAG 2013:** $\tau_{B_s}/\tau_{B_d} = 0.998 \pm 0.009$
- 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

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

$\Rightarrow$ 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: NLO-QCD + Lattice

Finally $\Delta\Gamma_s$ is measured!

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

A.L., Nierste 1102.4274

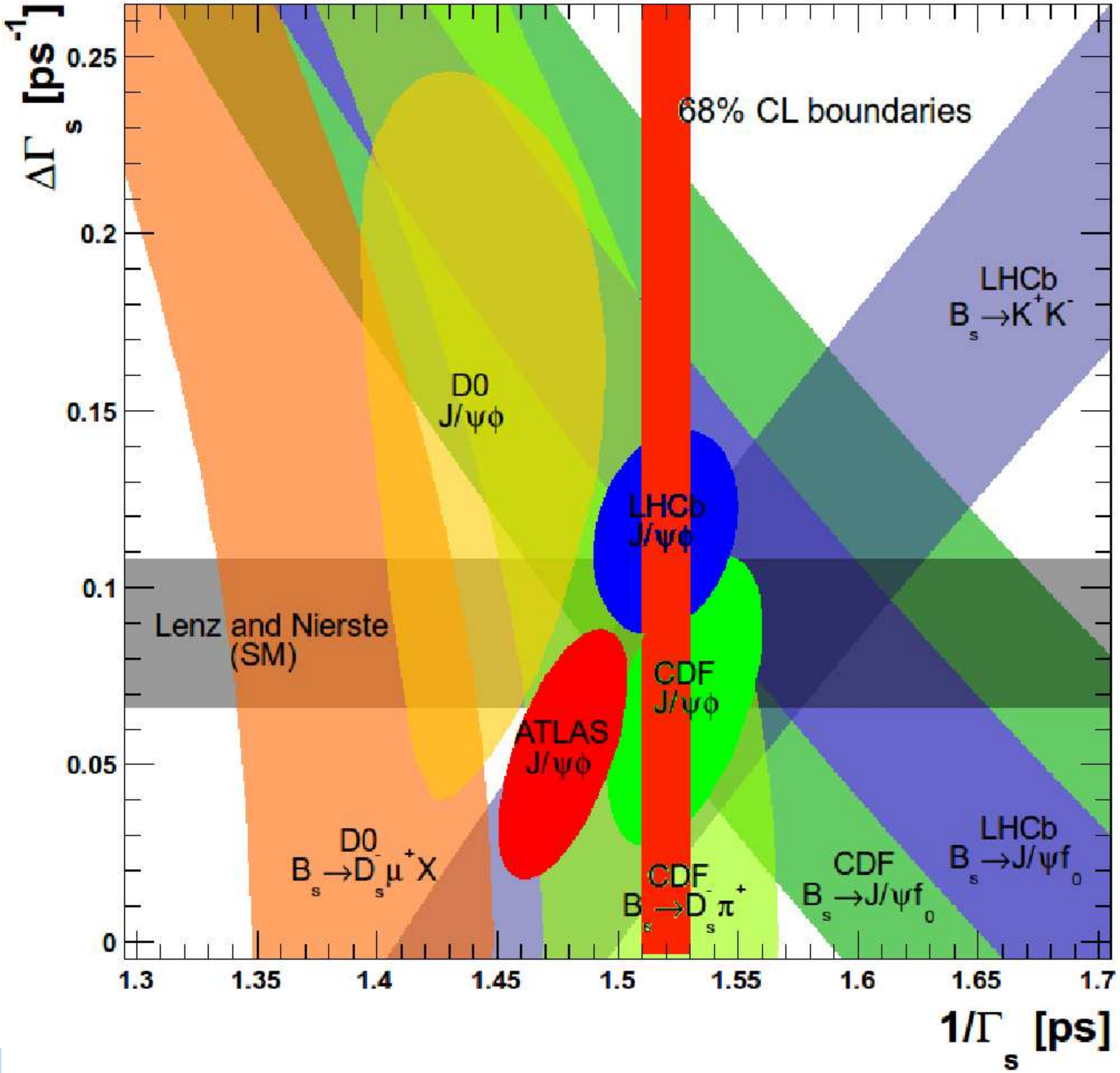
Mostly from angular analysis of $B_s \to J/\psi\phi(K+K-)$ Dunietz, Fleischer, Nierste,
but also $B_s \to J/\psi\pi^+\pi^-$

$\Delta\Gamma_s = (0.100 \pm 0.016)\,\text{ps}^{-1}$	:	LHCb 1304.2600
$\Delta\Gamma_s = (0.116 \pm 0.019)\,\text{ps}^{-1}$	:	LHCb-Conf-2012-002 $> 5\sigma!$
$\Delta\Gamma_s = (0.163 \pm 0.065)\,\text{ps}^{-1}$	:	D0 8fb^{-1} 1109.3166
$\Delta\Gamma_s = (0.068 \pm 0.027)\,\text{ps}^{-1}$	:	CDF 9.6fb^{-1} 1208.2967
$\Delta\Gamma_s = (0.053 \pm 0.022)\,\text{ps}^{-1}$	:	ATLAS 4.9 fb^{-1} 1208.0572

$$\Delta\Gamma_s^{Exp} = (0.081 \pm 0.011)\,\text{ps}^{-1}$$

HFAG 2013

Finally $\Delta\Gamma_s$ is measured!



Thanks to Roger Jones

Test of our theoretical Understanding

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

LHCb Moriond 2012, 2013; ATLAS; CDF; DO

$$\Delta\Gamma_s^{\text{Exp}} = (0.081 \pm 0.011)\,\text{ps}^{-1}$$
$$\Delta\Gamma_s^{\text{SM}} = (0.087 \pm 0.021)\,\text{ps}^{-1}$$

HFAG 2013

A.L.,Nierste 1102.4274

Cancellation of non-perturbative uncertainties in ratios

$$\left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^{\text{Exp}} / \left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^{\text{SM}} = 0.92 \pm 0.12 \pm 0.20$$

Dominant uncertainty = NNLO-QCD + Lattice

Test of our theoretical Understanding

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)
- Violation quark hadron duality: Theoreticians were fighting for 35 years

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

Still more accurate data needed!

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

1. Apply HQE also to $b \to c\bar{c}s$ transitions
2. Apply HQE to quantities that are sensitive to NP
3. Apply HQE also to quantities in the charm system?

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Search for New Physics in B-mixing

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

$$a_{fs}^s = (1.9 \pm 0.3) \cdot 10^{-5} \qquad \phi_s = 0.22^\circ \pm 0.06^\circ$$

$$a_{fs}^d = -(4.1 \pm 0.6) \cdot 10^{-4} \qquad \phi_d = -4.3^\circ \pm 1.4^\circ$$

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

$$\left|\frac{\Delta\Gamma_d}{\Gamma_d}\right| = (4.2 \pm 0.8) \cdot 10^{-3}$$

Older experimental bounds:

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

$$\left|\frac{\Delta\Gamma_d}{\Gamma_d}\right| = (15 \pm 18) \cdot 10^{-3}$$ **(HFAG 13)**

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

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

Search for New Physics in B-Mixing

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

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

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

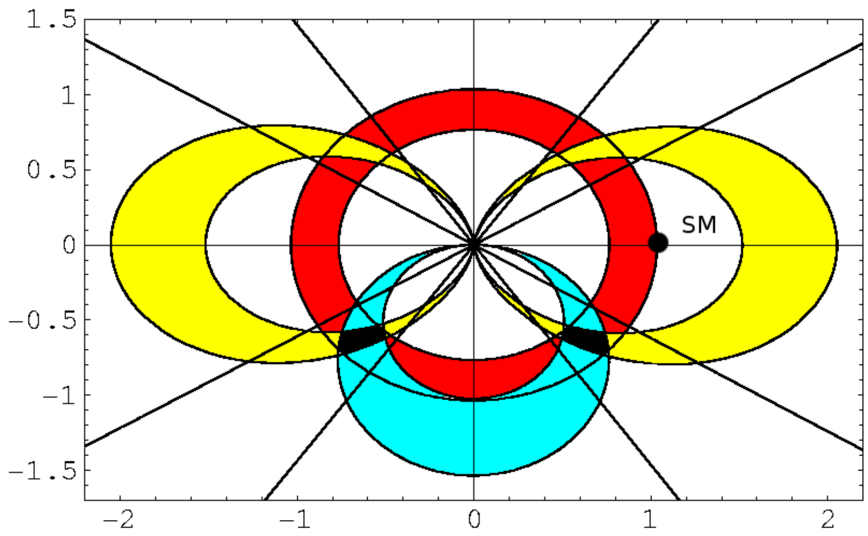
$$\Delta\Gamma_s = 2|\Gamma_{12,s}| \cdot \cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)$$

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

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

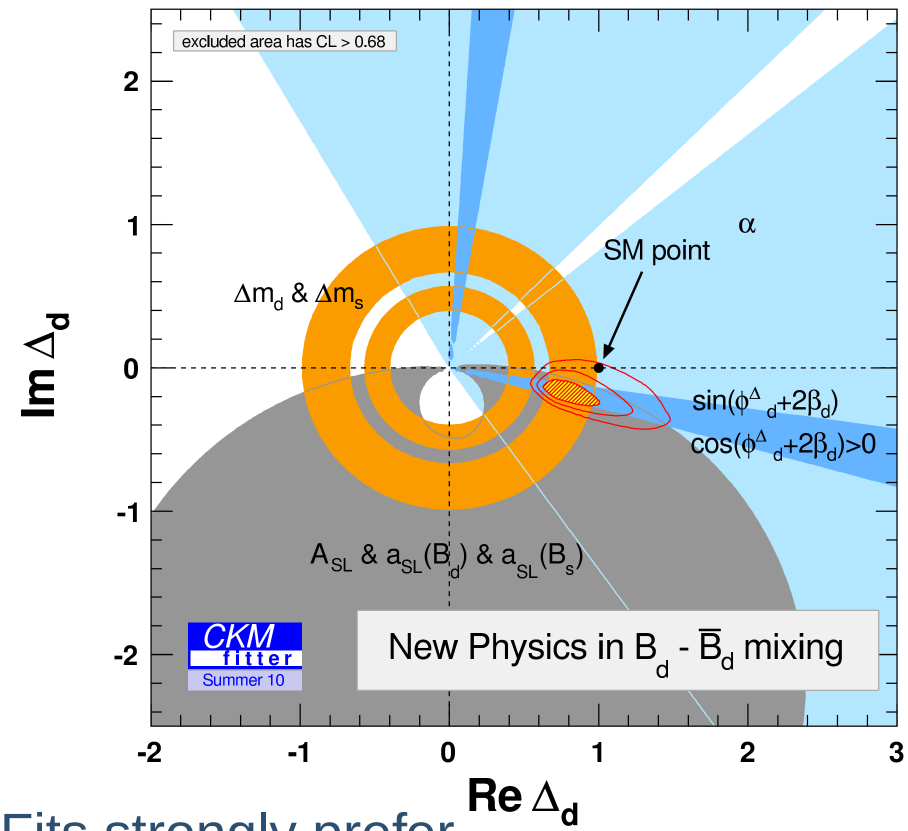
$$\sin(\phi_s^{\rm SM}) \approx 1/240$$

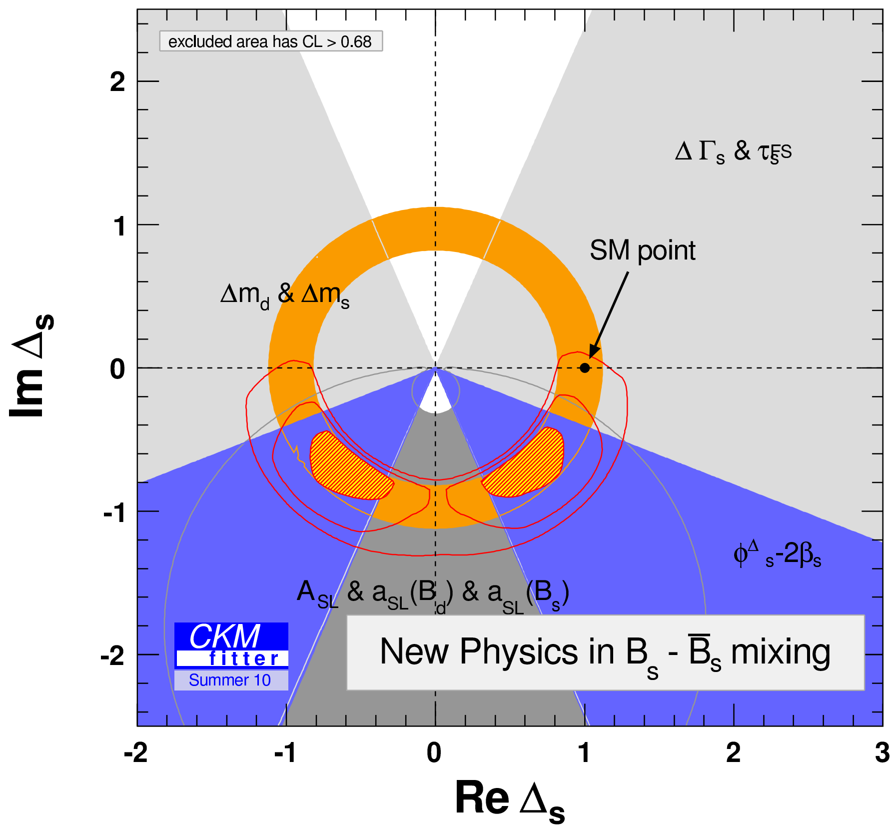
For $|\Delta_s| = 0.9$ and $\phi_s^\Delta = -\pi/4$ one gets the following bounds in the **complex Δ-plane**:



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

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



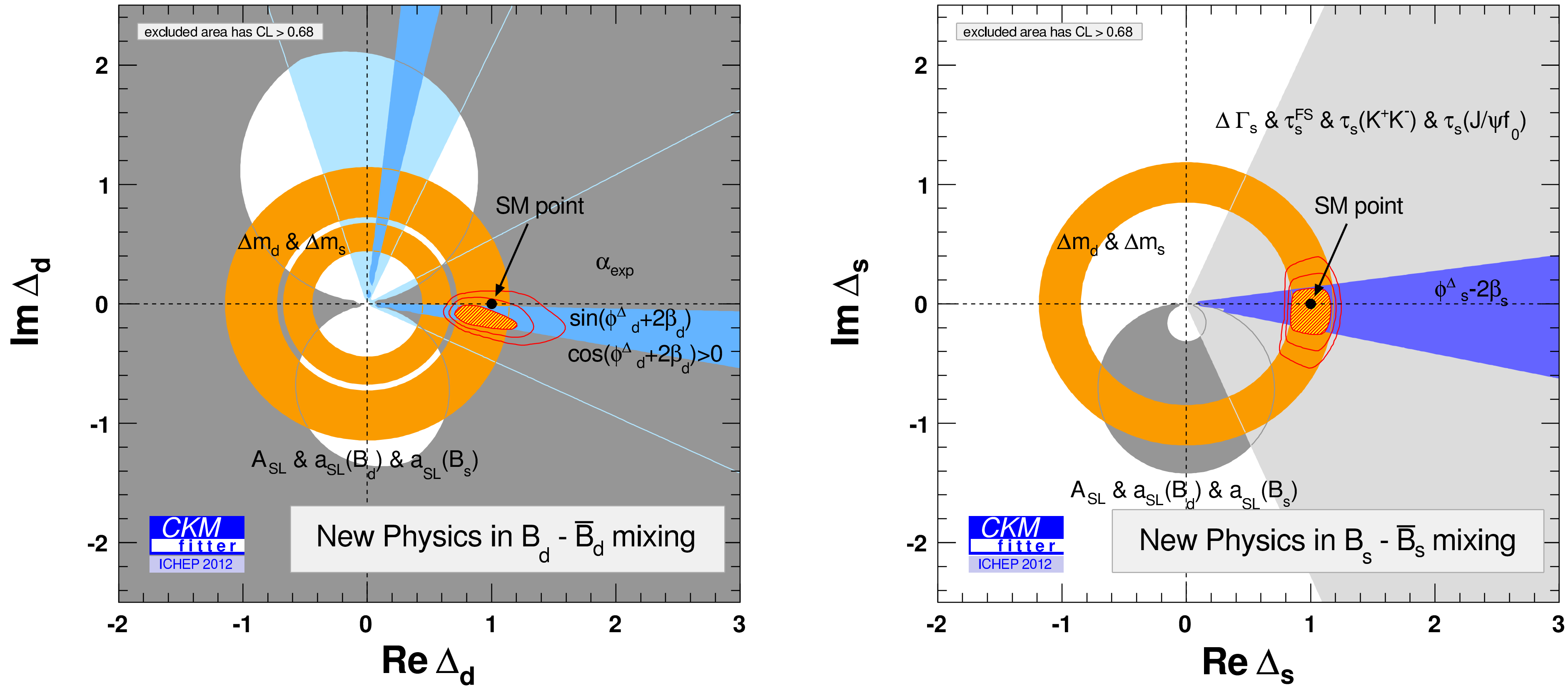


Fits strongly prefer

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

Search for New Physics in B-Mixing

unpublished: Combine all data till end of 2012 and neglect penguins
fit of Δ_d and Δ_s; update of A.L., Nierste, CKMfitter 1203.0238v2



- SM seems to be perfect
- Still quite some room for NP

Thanks to CKMfitter!

Search for NP in B-Mixing: A_{sl}^b?

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

BUT: The experimental number is larger than "possible"! A.L. 1205.1444, 1106.3200

1. Huge (= several 100 $\%$) duality violations in Γ_{12}? $\rightarrow$ 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**

Search for NP in B-Mixing: A^b_{sl}?

- New measurements for the individual semi leptonic CP asymmetries

$$a^s_{sl} = -0.06 \pm 0.50 \pm 0.36\%$$ **LHCb 1308.1048**

$$a^s_{sl} = -1.12 \pm 0.74 \pm 0.17\%$$ **D0 1207.1769**

$$a^d_{sl} = 0.68 \pm 0.45 \pm 0.14\%$$ **D0 1208.5813**

$$a^d_{sl} = 0.06 \pm 0.17^{+0.38}_{-0.32}\%$$ **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**

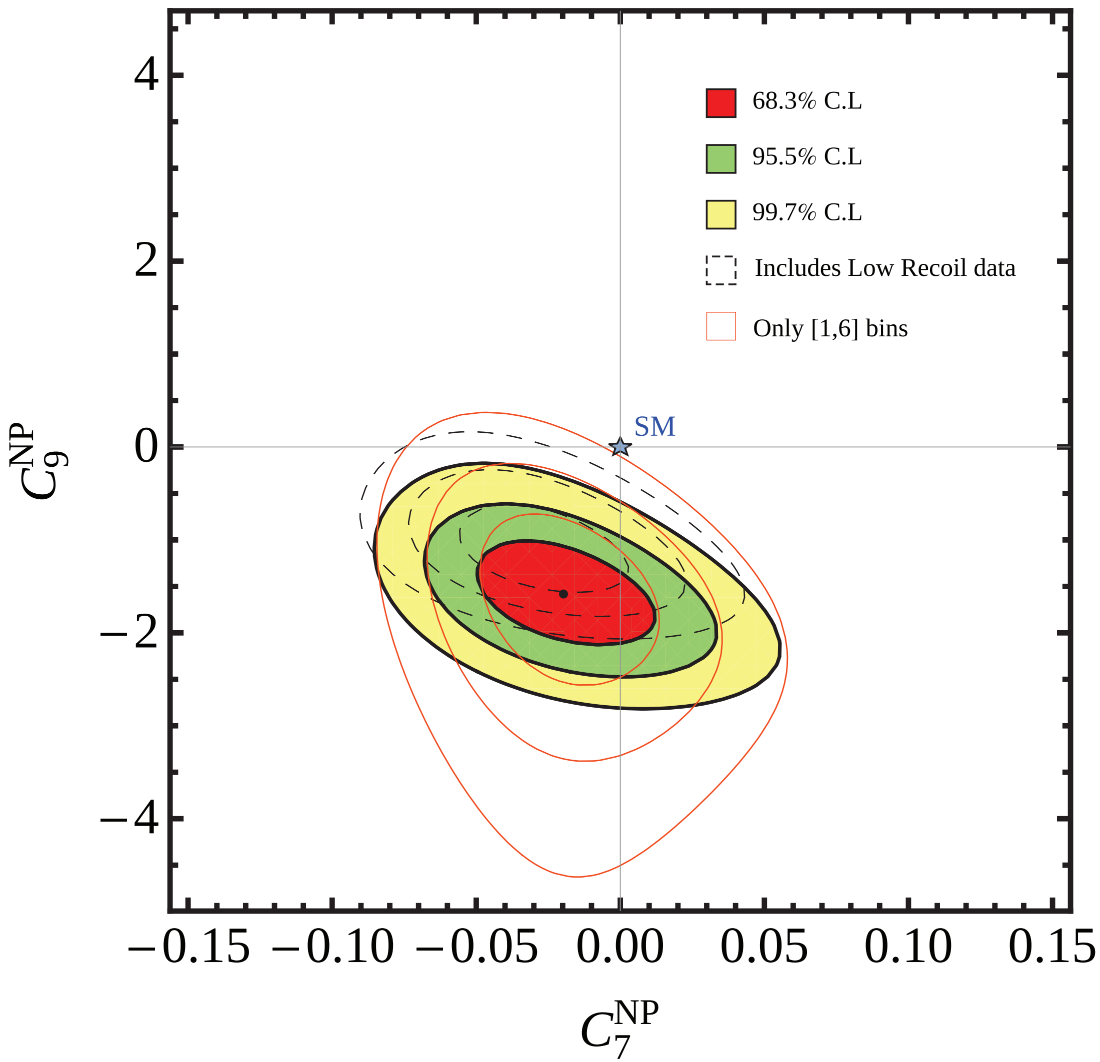
$$A^b_{sl} = C_d a^d_{sl} + C_s a^s_{sl} + C_\Gamma \frac{\Delta\Gamma_d}{\Gamma_d}$$

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

Search for New Physics in $b \to sll$ transitions

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

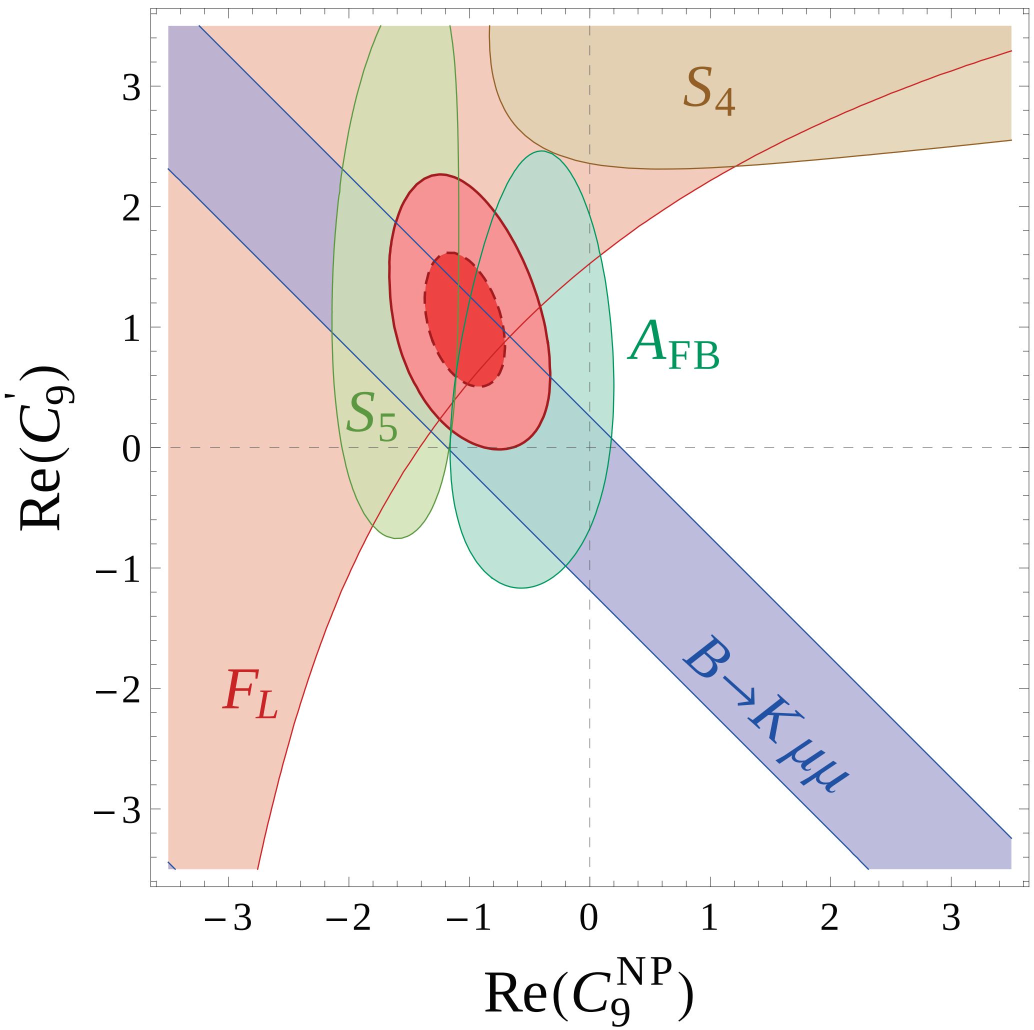
1. **Descotes-Genon, Matias, Virto - 1307.5683**



Search for New Physics in $b \to sll$ transitions

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

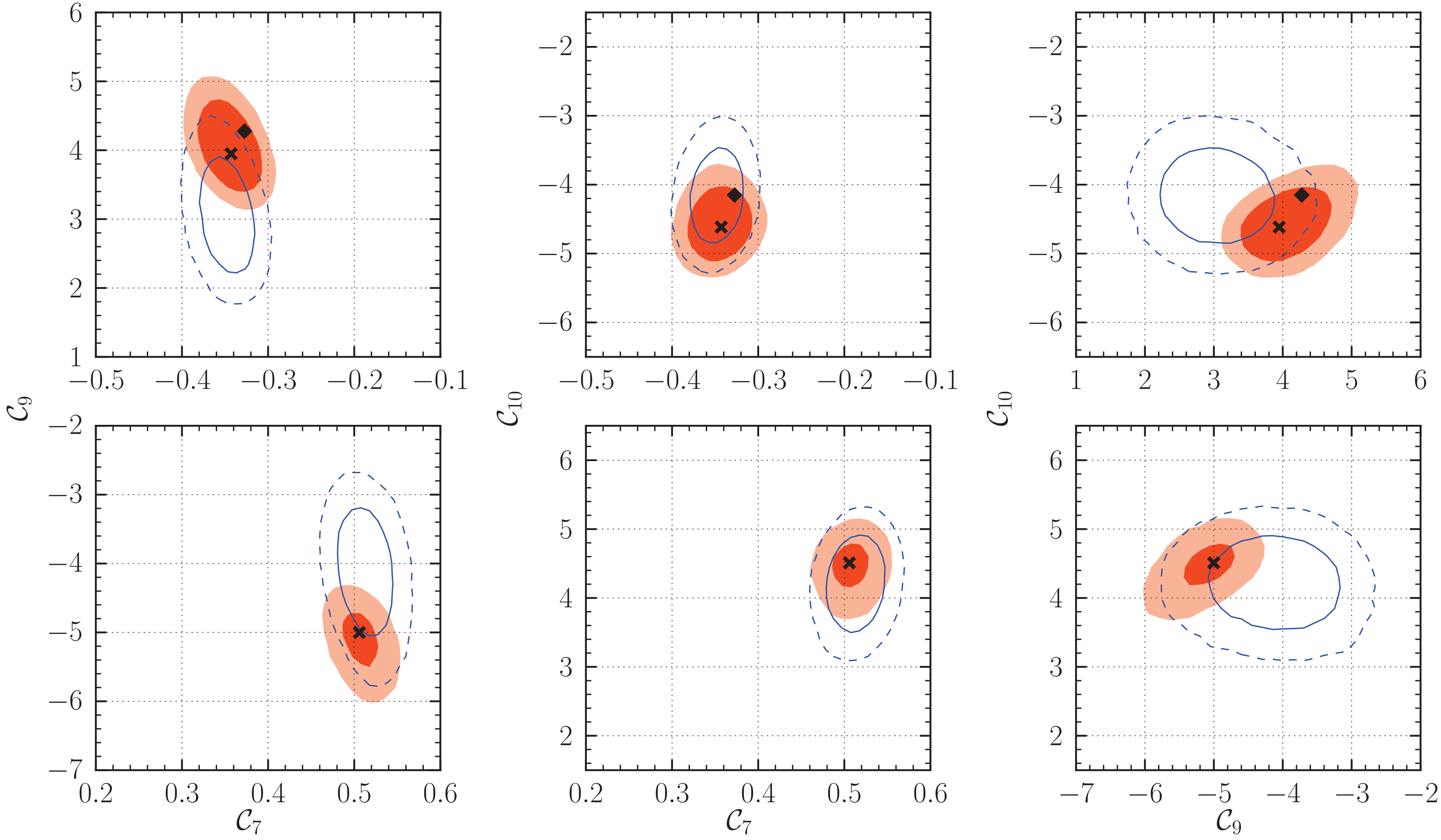
2. **Altmannshofer, Straub - 1308.1501**



Search for New Physics in $b \to sll$ transitions

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

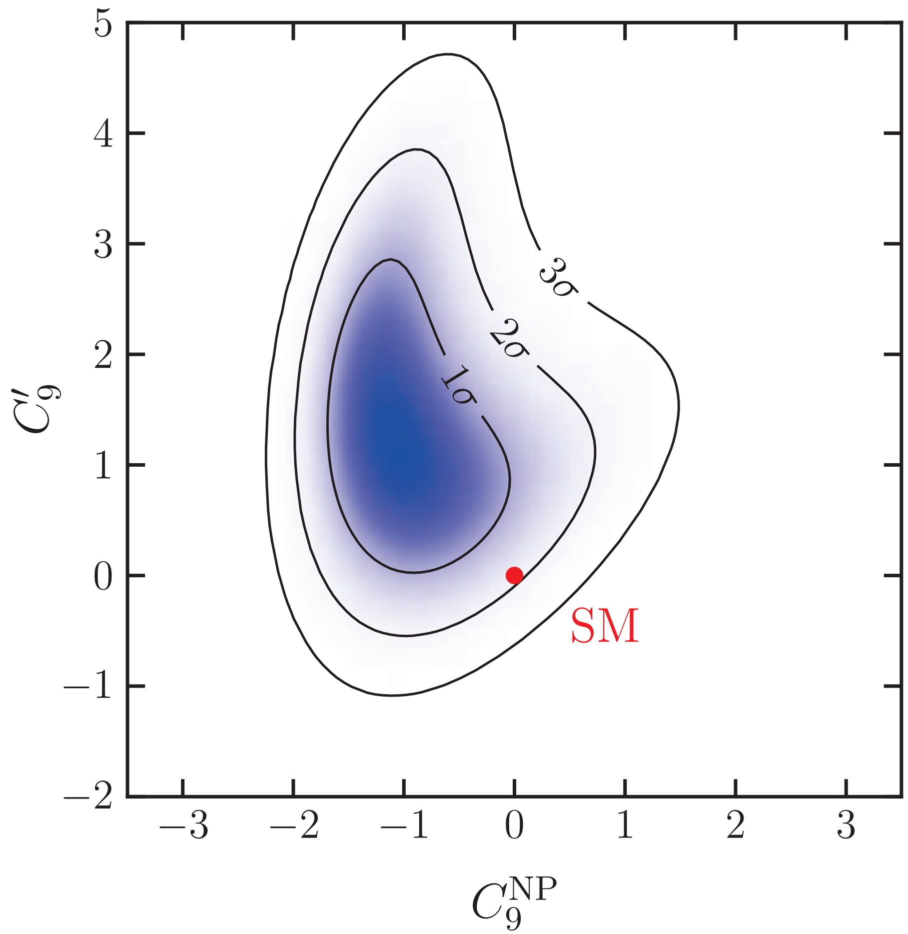
3. **Beaujean, Bobeth, van Dyck - 1310.2478**



Search for New Physics in $b \to sll$ transitions

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

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



New physics in flavour observables:

What did we learn from current NP searches?

1. A lot of observables look **SM like**, e.g. $B_s \to \mu\mu$
2. There are **no huge NP effects**, e.g. $\phi_s \ll 45°$ - Was this to be expected?
3. Still **sizable NP effects possible, even in** $B_s \to \mu\mu, \phi_s$:-)
   Several interesting discrepancies at the 3 σ level
   - $B \to K^* \mu\mu$
   - $B \to D^{(*)} \tau\nu$
   - $a_{sl}^d, a_{sl}^s, \Delta\Gamma_d$
   - V_{ub}
   - ...

$\Rightarrow$ Life is not as easy as hoped for

higher precision in experiment and theory needed

- Perturbative and hadronic uncertainties have to be controlled
- Neglecting penguin contributions might not be appropriate any more

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?
  - Test of our theoretical Understanding
  - Search for New Physics
  - The second Charm Revolution
- Some Roads to follow
  - Test of our theoretical Understanding
  - Search for New Physics
  - Explore the Charm Sector
- Conclusion

HQE at its or beyond its limits?

- '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

What did we really learn?

- Test of our theoretical Understanding
  - SM and CKM work perfectly
  - Theoretical tools (HQE) work also perfectly (at least to about 30% for most dangerous modes $\Delta\Gamma_s^{\rm SM} = \Delta\Gamma_s^{\rm Exp.}$) - this was unclear for a long time
- Search for NP - **Missing CPV for the origin of matter in the universe still not identified**
  - No huge effects, but still some sizable space (mixing, rare decays,...)

    look for new extraction strategies
  - Several interesting discrepancies - e.g. $B \to K^* \mu\mu, A_{sl}, B \to D\tau\nu, V_{ub}$,...
  - NP models can not always evade their death

    combine flavour constraints with electro-weak and Higgs constraints
- The Charm Sector might be very interesting
  - Understand SM background - Test of applicability of theoretical tools
  - First results very promising Uncertainties dominated by hadronic quantities
- **Life becomes harder: higher precision in experiment and theory needed**
  - **Calculate perturbative corrections**
  - **Calculate non-perturbative corrections - lattice**
  - **Look for new experimental strategy - Monte Carlo**
  - **Use alternative non-perturbative methods (LCSR,...)**

Some roads to follow

- Further Test of our theoretical Understanding
  - Precision test of b-hadron lifetimes: How precise is the HQE? Crucial!
  - Precise determination of Γ_{12}: Is there some NP in Γ_{12}?
  - Penguin contributions: Is there some NP in penguins?
- Search for New Physics (NP)
  - Model independent search with inclusive non-leptonic decays
  - Investigate badly constrained modes, like $B_{d,s} \to \tau\tau, \Delta\Gamma_d, B \to K/\pi\tau\tau$,...
  - Model dependent investigations (e.g. 2HDM, Z', RS, LQ, SUSY,...)
- Explore the Charm Sector
  - Lifetimes of charmed mesons and baryons: Does HQE work for charm?
  - Investigation of Mixing: Is there NP in charm mixing?

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

Year	Exp	Decay	$\tau(\Lambda_b)$ [ps]	$\tau(\Lambda_b)/\tau(B_d)$
2013	HFAG	average	1.429 ± 0.024	0.941 ± 0.016
2013	LHCb	$J/\psi p K^-$	1.482 ± 0.022	0.976 ± 0.012
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	$0.74 \pm 0.24*$

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

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

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

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

Numbers from **Bigi, Mannel Uraltsev**, 2011

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

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

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**
- Matrix element
  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**: $\tau_{\Lambda_b}/\tau_{B_d} > 0.9$ **AL 1205.1444**

$$\Rightarrow r = 0.68 \pm 0.08$$

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

1999 **DiPierro, Sachrajda, Michael**:

currently the only lattice determination!

- **14 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...

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
- Get rid of unwanted $s \to u$-transitions

$$\frac{1}{\bar{\tau}(\Xi_b)} = \bar{\Gamma}(\Xi_b) = \Gamma(\Xi_b) - \Gamma(\Xi_b \to \Lambda_b + X)\,.$$

Analytic result given in **Beneke, Buchalla, Greub, AL, Nierste 2002**

$$\frac{\bar{\tau}(\Xi_b^0)}{\bar{\tau}(\Xi_b^+)} = 1 - 0.12 \pm 0.02 \pm ???\,,$$

AL 0802.0977

$???$ unknown systematic hadronic errors.

Further assume $\bar{\tau}(\Xi_b^0) = \tau(\Lambda_b)$ - similar cancellations as in τ_{B_s}/τ_{B_d}

$$\frac{\tau(\Lambda_b)}{\bar{\tau}(\Xi_b^+)} = 0.88 \pm 0.02 \pm ???\,.$$

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  - Precision test of b-hadron lifetimes: How precise is the HQE? Crucial!
  - Precise determination of Γ_{12}: Is there some NP in Γ_{12}?
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  - Model independent search with inclusive non-leptonic decays
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  - Model dependent investigations (e.g. 2HDM, Z', RS, LQ, SUSY,...)

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How large are Penguins?

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

$$S_{\psi\phi}^{\rm SM} = 0.0036 \pm 0.002 \to \sin\left(2\beta_s - \phi_s^{\Delta} - \delta_s^{\rm Peng,SM} - \delta_s^{\rm Peng,NP}\right) = 0.01 \pm 0.07$$

LHCb Moriond 2013

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**

How large are Penguins?

Many observables in the B_s mixing system:

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

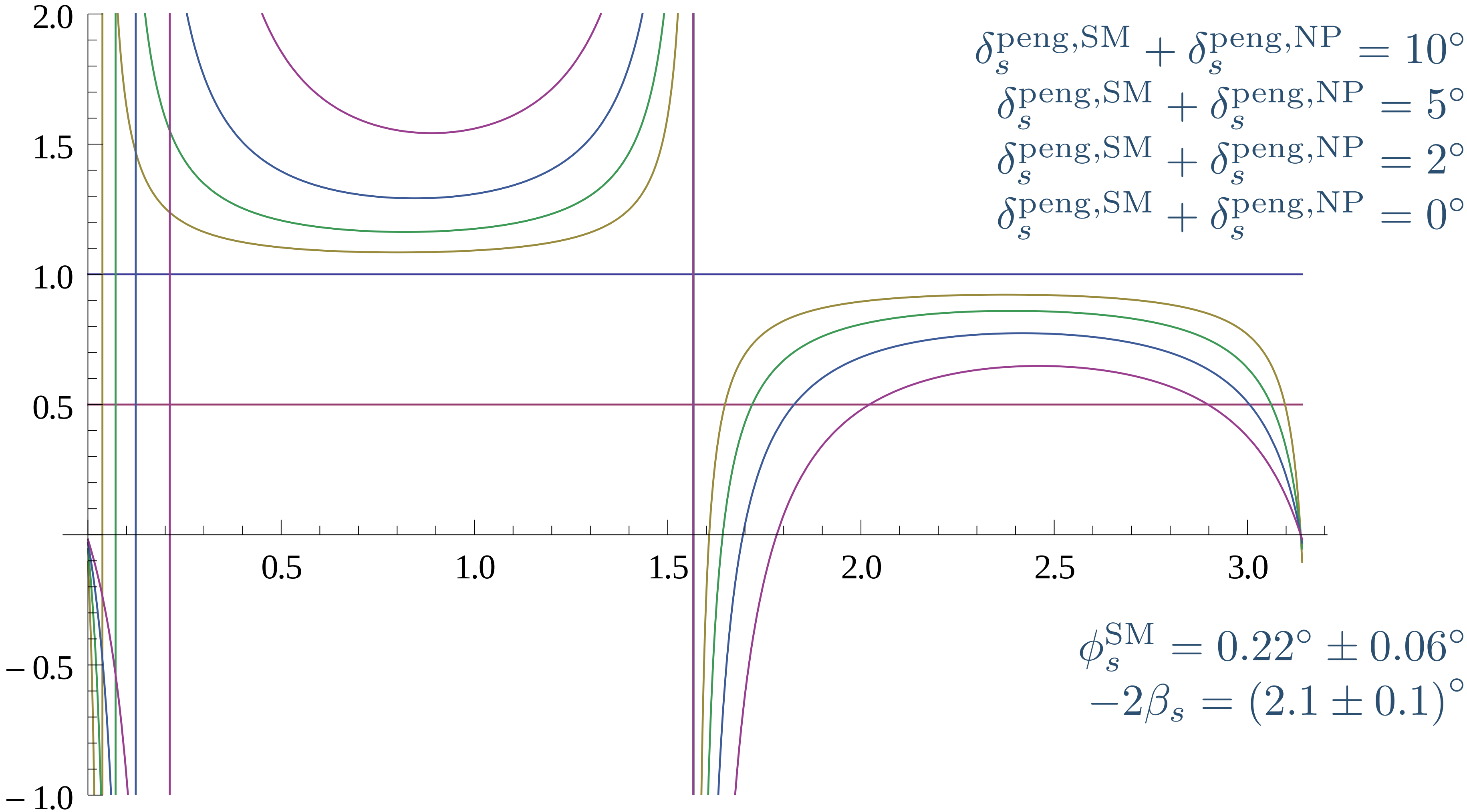
$$a_{sl}^s = -\frac{\Delta\Gamma}{\Delta M}\frac{S_{\psi\phi}}{\sqrt{1-S_{\psi\phi^2}}}\cdot\delta$$

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

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

A.L. 1106.3200

How large are Penguins?



- 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

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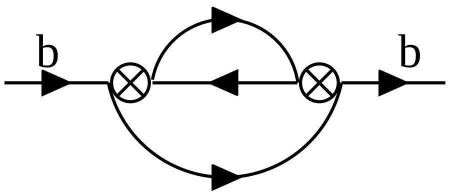
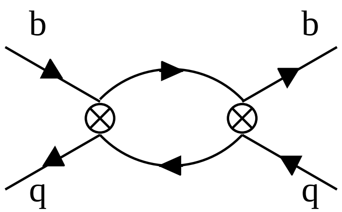
Promising alternatives to search for NP?

Motivated by the original discrepancy in A_{sl}^b
Can there be large $\mathcal{O}(200 - 3400\%)$ NP effects in Γ_{12}^s? **NO!**

- 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.:
  - 

    $$\Gamma_0 \Rightarrow \begin{cases} \tau(B_x) \\ B_{sl} \\ Br(b \to s + 0, 1, 2 \text{ charm}) \end{cases}$$

  - 

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

  - M_{12}, operator mixing with e.g. $b \to s\gamma$, ...
  - A promising candidate for X seems to be $\tau^+ + \tau^-$ -> **Bobeth, Haisch '11**. Current direct bound $Br(B_s \to \tau\tau < 5\%)$ - **LHCb, Belle** should do better
    At most $\mathcal{O}(30\%)$ effects in Γ_{12}^s possible via $B_s \to \tau\tau \equiv$ very big NP effect!
  - **Can there be some other "hidden" or enhanced channels?**

Search for hidden NP decays I

Now: Model and even decay channel independent

A new $b \to X$ contribution
would modify inclusive decay rates in the following form:

$$\Gamma = \Gamma_0 + \left(\frac{\Lambda}{m_b}\right)^2 \Gamma_2 + \left(\frac{\Lambda}{m_b}\right)^3 \Gamma_3 + ...$$

$$\Rightarrow \Gamma = \Gamma_0 + \delta_b + \left(\frac{\Lambda}{m_b}\right)^2 \Gamma_2 + \left(\frac{\Lambda}{m_b}\right)^3 \Gamma_3 + \delta_B + ...$$

where δ_b is a universal contribution to all b-decays,
while δ_B is a specific contribution in the decay of a B-meson.

This affects different observables differently

Search for hidden NP decays II

- **Lifetime ratios:**

$$\frac{\tau(B_2)}{\tau(B_1)} = \frac{\Gamma(B_1)}{\Gamma(B_2)} = \frac{\Gamma_0 + \delta_b + \left(\frac{\Lambda}{m_b}\right)^2 \Gamma_2 + \left(\frac{\Lambda}{m_b}\right)^3 \Gamma_3(B_1) + \delta_{B_1} + ...}{\Gamma_0 + \delta_b + \left(\frac{\Lambda}{m_b}\right)^2 \Gamma_2 + \left(\frac{\Lambda}{m_b}\right)^3 \Gamma_3(B_2) + \delta_{B_2} + ...}$$

$$\approx 1 + \left(\frac{\Lambda}{m_b}\right)^3 \frac{\Gamma_3(B_1) - \Gamma_3(B_1)}{\Gamma_0} + \frac{\delta_{B_1} - \delta_{B_2}}{\Gamma_0}$$

Insensitive to δ_b

- **Semi leptonic branching ratio:**

$$B_{sl} = \frac{\Gamma_{sl} + \delta_{sl}}{\Gamma_0 + \delta}$$

Sensitive to δ_{sl} and $\delta = \delta_b + \delta_B$

- **Inclusive branching ratios:**

$$B(b \to 0, 1, 2 \text{ charm}) = \frac{\Gamma(b \to 0, 1, 2 \text{ charm}) + \delta_{0,1,2}}{\Gamma_0 + \delta}$$

Sensitive to $\delta_{0,1,2}$ and $\delta = \delta_b + \delta_B = \delta_0 + \delta_1 + \delta_2$

Search for hidden NP decays III

In the 90ies: **Missing charm puzzle; semi leptonic branching fraction**, 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-decays into 0, 1, 2 c-quarks
The average number of charm quarks per b-decay reads

$$\begin{aligned} n_c &= 0 + [Br(1\text{ charm}) + 2Br(2\text{ charm})] \\ &= 1 + [Br(2\text{ charm}) - Br(0\text{ charm})] \\ &= 2 - [Br(1\text{ charm}) + 2Br(0\text{ charm})] \end{aligned}$$

get rid of “2c”: **Buchalla, Dunietz, Yamamoto '95**

- **The missing charm puzzle:**

$$n_c^{\text{Exp.}} \in [0.93; 1.23] \quad < \quad n_c^{\text{Theory}} \in [1.15; 1.33]$$
$$B_{sl}^{\text{Exp.}} \approx 0.105 \quad < \quad B_{sl}^{\text{Theory}} \approx 0.12$$

Popular interpretations:

- May be enhanced $b \to s\ g$ rate due to new physics... **Kagan ...**
- Quark hadron duality might be violated in $b \to c\bar{c}s$

Search for hidden NP decays IV

Any unknown, even invisible decay mode has an effect on $Br(0, 1, 2\ \text{charm})$

Investigation of $B_{sl}, Br(0, 1, 2\ \text{charm}), \tau(B_1)/\tau(B_2)$ and n_c gives model- and even decay channel independent constraints on NP models!

Remember: there is still some space for NP!

Investigation of inclusive decays is worth some effort!

Search for hidden NP decays V

- Theory: (Motivation for an update - latest one from 1998)
  - NLO-QCD for $b \to c\bar{u}d, c\bar{c}s$ stems from 1994/95;
    Bagan, Ball, Braun, Fiol, Gosdzinsky
    - Knowledge about many input parameters (e.g. $m_b, m_c, V_{CKM}, ...$) has improved dramatically in the last 18 years.
    - No sizable duality violations are expected to occur in $b \to c\bar{c}s$
  - Many rare decays were neglected, e.g. $b \to sg, b \to u\bar{u}s, ...$
  - Some NLO-QCD contributions are still missing

- Experiment: (Motivation for an update)
  - Latest experimental still stem from BaBar and CLEO and LEP!
    New experiments should be able to do better! **BaBar; hep-ex/0606026**
  - Inclusive decays are theoretically nice but experimentally very difficult
    Monte Carlo (Sherpa) investigations just started with **Frank Krauss + Gilberto Tetlalmatzi-Xolocotz, Stefanos Tyros, Ashley Harrison**

Search for hidden NP decays VI

My idea: Let some students programme all the NLO-QCD formulae and perform a new analysis with up-to-date input parameters, **BUT:**

- Semi leptonic decays **Hokim, Pham; Nir** (1984, 1989) ok
- $b \to c\bar{u}d$ **Bagan, Ball, Braun, Gosdzinsky** (1994) ok
- $b \to c\bar{c}s$ **Bagan, Ball, Fiol, Gosdzinsky** (1995) **not ok!!!**
  - Literature contains several misprints (result is e.g. not IR finite)
  - Authors left physics, retired, do now Quantum computing, programmes do not run anymore ...
  - Recalculation with students at TU Munich finished
    Also some new contributions included **Krinner, A.L., Rauh; 1305.5390**
- $b \to u\bar{u}d, u\bar{u}s, s\bar{s}s, s\bar{s}d, d\bar{d}d, d\bar{d}s$ **A.L., Nierste, Ostermaier** (1997) ok
- $b \to sg$ **Greub, Liniger** (2000) ok

Search for hidden NP decays VII

Next steps:

- Combined phenomenological analysis of $B_{sl}; Br(0, 1, 2 \text{ charm})$ and $\tau(B_1)/\tau(B_2)$ to determine the remaining space for new physics effects in inclusive b-decays

  Theoretical accuracy of the branching ratios of about $10 - 15\%$

  Kagan, Krinner, A.L., Nierste, Rauh; in prep.

- New experimental analysis
  Latest result from **BaBar; hep-ex/0606026**

$$n_c(B^-) = 1.208 \pm 0.056$$
$$n_c(B_d) = 1.203 \pm 0.060$$

  This corresponds to about 30% accuracy in $Br(2 \text{ charm})$

- Inclusive decays are theoretically nice but experimentally very difficult
  Preliminary Monte Carlo (Sherpa) investigations started **Frank Krauss + Gilberto Tetlalmatzi-Xolocotz, Stefanos Tyros, Ashley Harrison**

Search for enhanced $b \to d, s\tau\tau$ transitions I

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** $\tau(B_s)/\tau(B_d)$

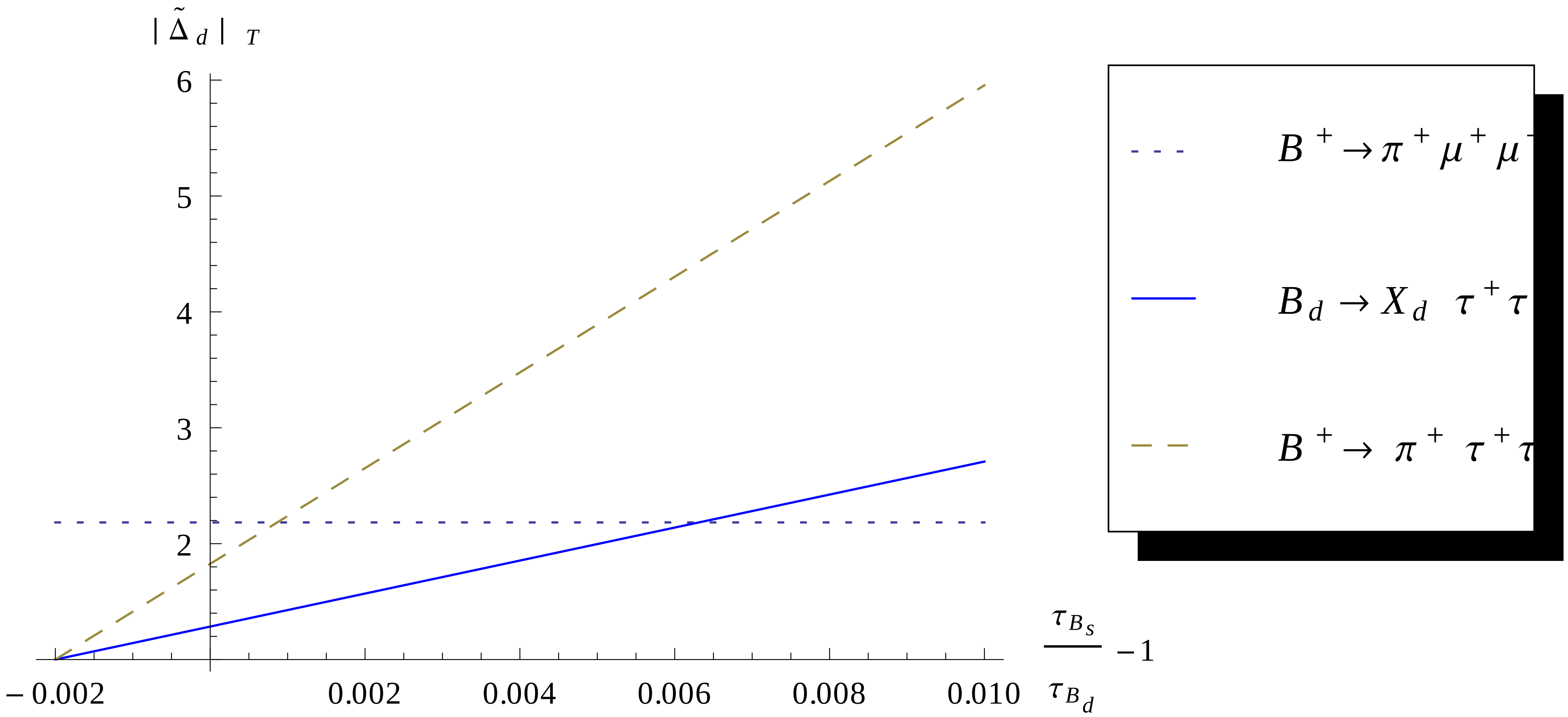
  $\Rightarrow$ Enhancement of up to **200**$\%$ in $\Delta\Gamma_d$ possible

This might solve the dimuon asymmetry! $\Rightarrow$ **Improve bounds on** $b \to d\tau\tau$**!**

Bobeth, Haisch, AL, Pecjak, Tetlalmatzi-Xolocotz, to appear

Search for enhanced $b \to d, s\tau\tau$ transitions II

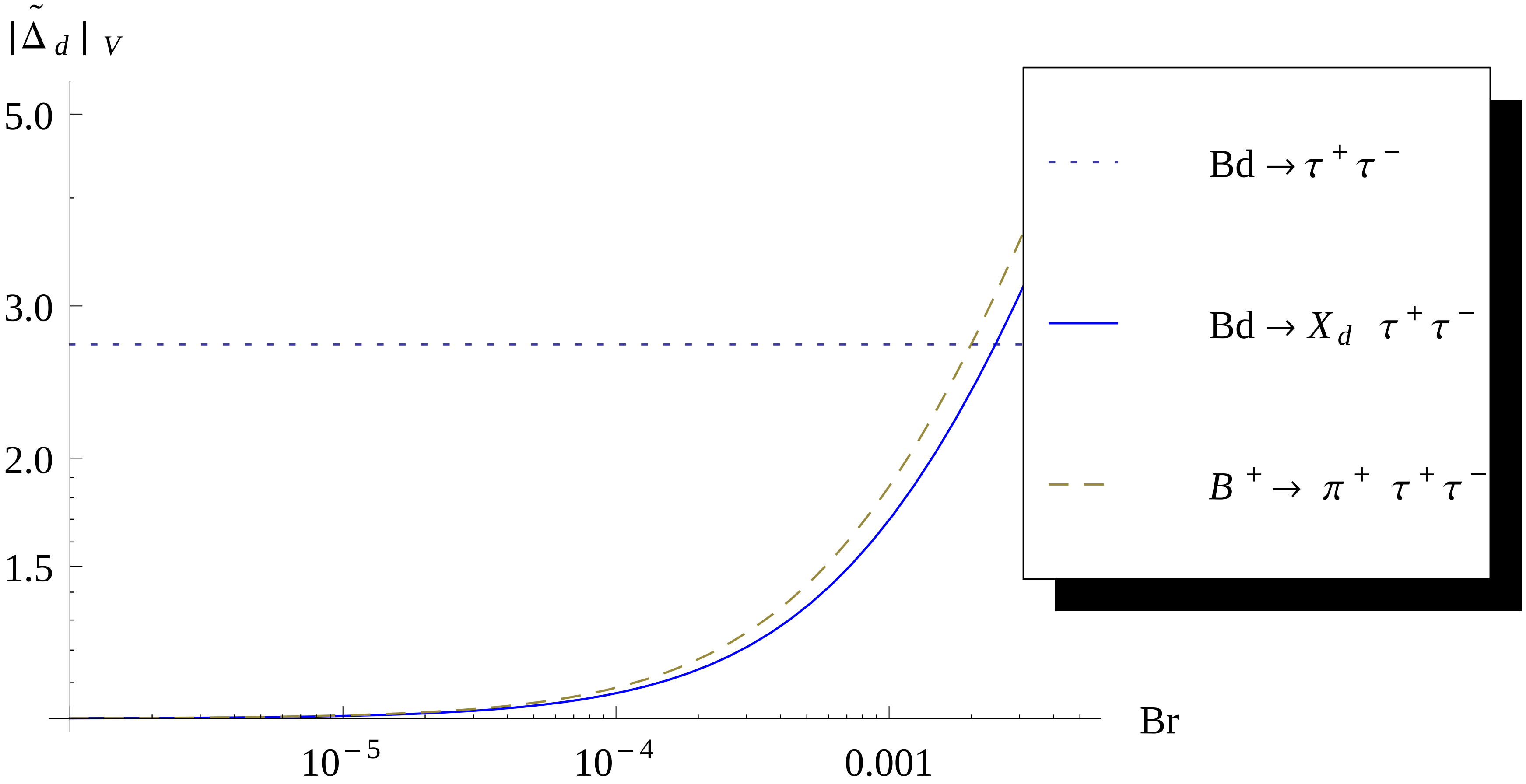
$\Delta\Gamma_d / \Delta\Gamma_d^{\rm SM}$ vs. precision in $\tau(B_s)/\tau(B_d)$



Bobeth, Haisch, AL, Pecjak, Tetlalmatzi-Xolocotz, to appear

Search for enhanced $b \to d, s\tau\tau$ transitions III

$\Delta\Gamma_d / \Delta\Gamma_d^{SM}$ vs. direct bounds on $b \to d\tau\tau$ transitions



Bobeth, Haisch, AL, Pecjak, Tetlalmatzi-Xolocotz, to appear

What did we really learn?

- Test of our theoretical Understanding
  - SM and CKM work perfectly
  - Theoretical tools (HQE) work also perfectly (at least to about 30% for most dangerous modes $\Delta\Gamma_s^{\rm SM} = \Delta\Gamma_s^{\rm Exp.}$) - this was unclear for a long time
- Search for NP - **Missing CPV for the origin of matter in the universe still not identified**
  - No huge effects, but still some sizable space (mixing, rare decays,...)

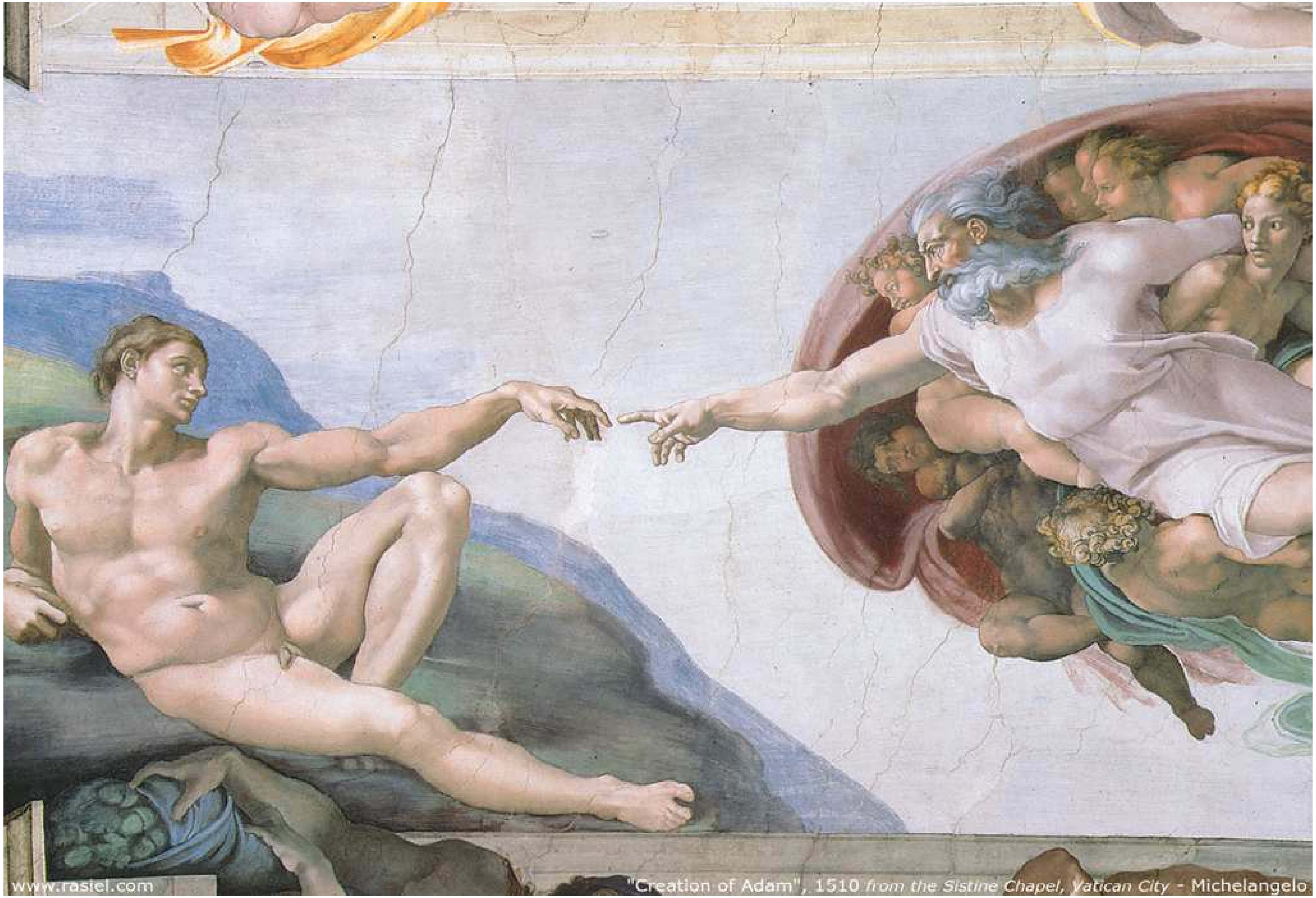
    look for new extraction strategies
  - Several interesting discrepancies - e.g. $B \to K^* \mu\mu, A_{sl}, B \to D\tau\nu, V_{ub}$,...
  - NP models can not always evade their death

    combine flavour constraints with electro-weak and Higgs constraints
- The Charm Sector might be very interesting
  - Understand SM background - Test of applicability of theoretical tools
  - First results very promising Uncertainties dominated by hadronic quantities
- **Life becomes harder: higher precision in experiment and theory needed**
  - **Calculate perturbative corrections**
  - **Calculate non-perturbative corrections - lattice**
  - **Look for new experimental strategy - Monte Carlo**
  - **Use alternative non-perturbative methods (LCSR,...)**

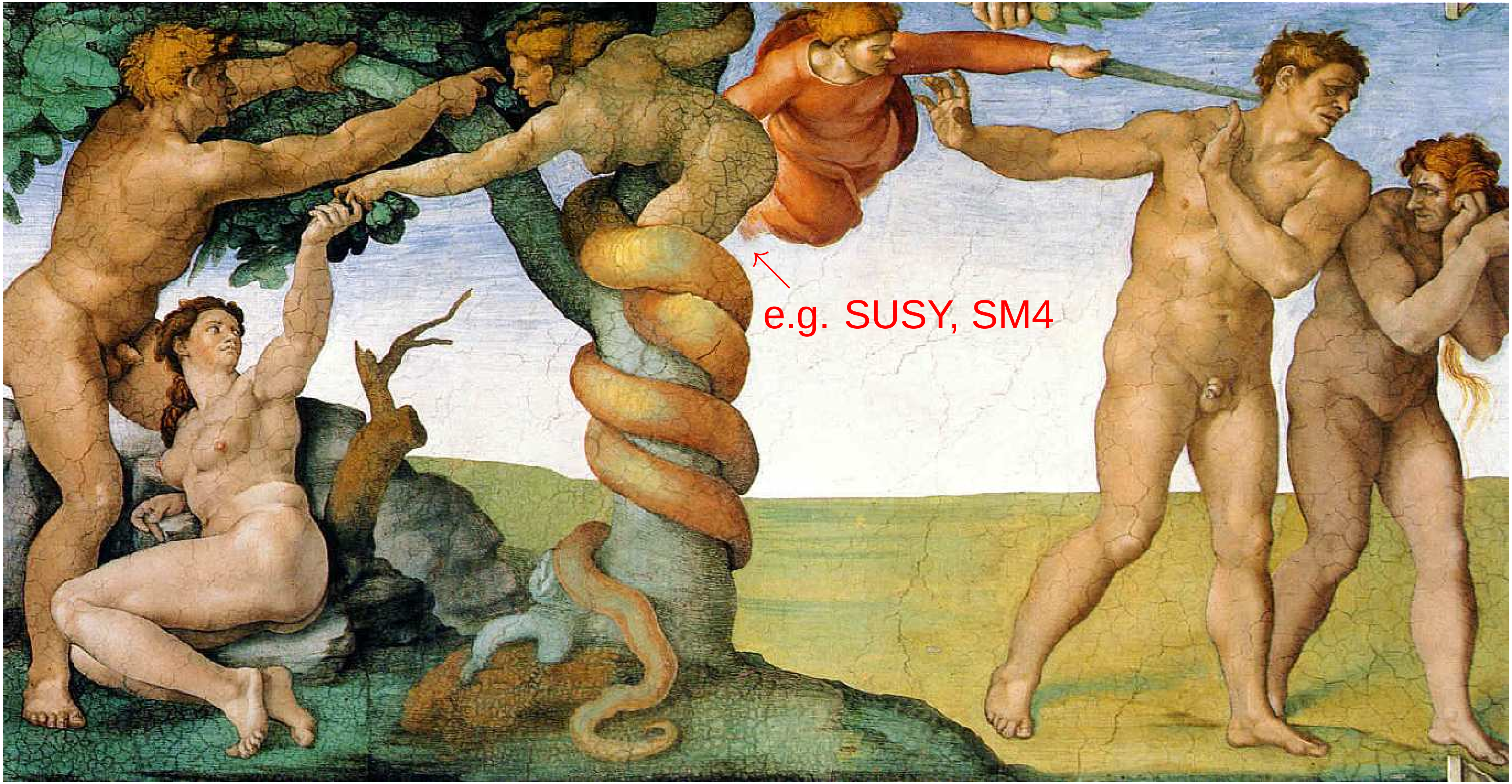
Some roads to follow

- Further Test of our theoretical Understanding
  - Precision test of b-hadron lifetimes: How precise is the HQE? Crucial!
    $\Rightarrow$ **Exp., Lattice, pert. QCD — precise** $\tau(B_d, B^+, B_s, \Lambda_b; \Xi_b)$
  - Precise determination of Γ_{12}: Is there some NP in Γ_{12}?
    $\Rightarrow$ **Exp., Lattice, pert. QCD — precise** $\Delta\Gamma_s$
  - Penguin contributions: Is there some NP in penguins?
    $\Rightarrow$ **Exp., Lattice?, sum rules?, pert. QCD — precise cross checks**
- Search for New Physics (NP)
  - Study persistent discrepancies: $a_{sl}^{s,d}, \Delta\Gamma_d, V_{ub}, B \to K^* \mu\mu, B \to D^{(*)} \tau\nu, ...$
    $\Rightarrow$ **Exp., Lattice?, sum rules?, pert. QCD,... — improve precision**
  - Model independent search with inclusive decays
    $\Rightarrow$ **Exp., pert. QCD, Monte Carlo— update for inclusive decays**
  - Investigate badly constrained modes, like $B_s \to \tau\tau, \Delta\Gamma_d$
    $\Rightarrow$ **Exp., pert. QCD, Monte Carlo— update on** $\Delta\Gamma_d, B_{d,s} \to \tau\tau; B \to K/\pi\tau\tau$**,...**
  - Model dependent investigations (e.g. 2HDM, Z', RS, LQ, SUSY,...)
- Explore the Charm Sector
  - Lifetimes of charmed mesons and baryons: Does HQE work for charm?
    $\Rightarrow$ **Exp., Lattice, pert. QCD**
  - Investigation of Mixing: Is there NP in charm mixing?
    $\Rightarrow$ **Exp., Lattice, pert. QCD**

FP ≡ A new clue to explain existence?



BUT: FP might also kill your favourite model



Coming UK Flavour Events

- November 14th - November 15th: **UK Hep Forum 2013**
  Abingdon
- January 8th - January 9th: **LHCb UK Meeting 2014**
  Durham
- July 21st - July 26th: **BEACH 2014**
  Birmingham
- xx.xx.2014: $B \to X_s ll$**-Workshop 2014**
  Imperial or Durham
- xx.xx.2015: **Heavy Flavour 2015**
  Distillery in Scotland?

More info: “Workshops” on IPPP webpage