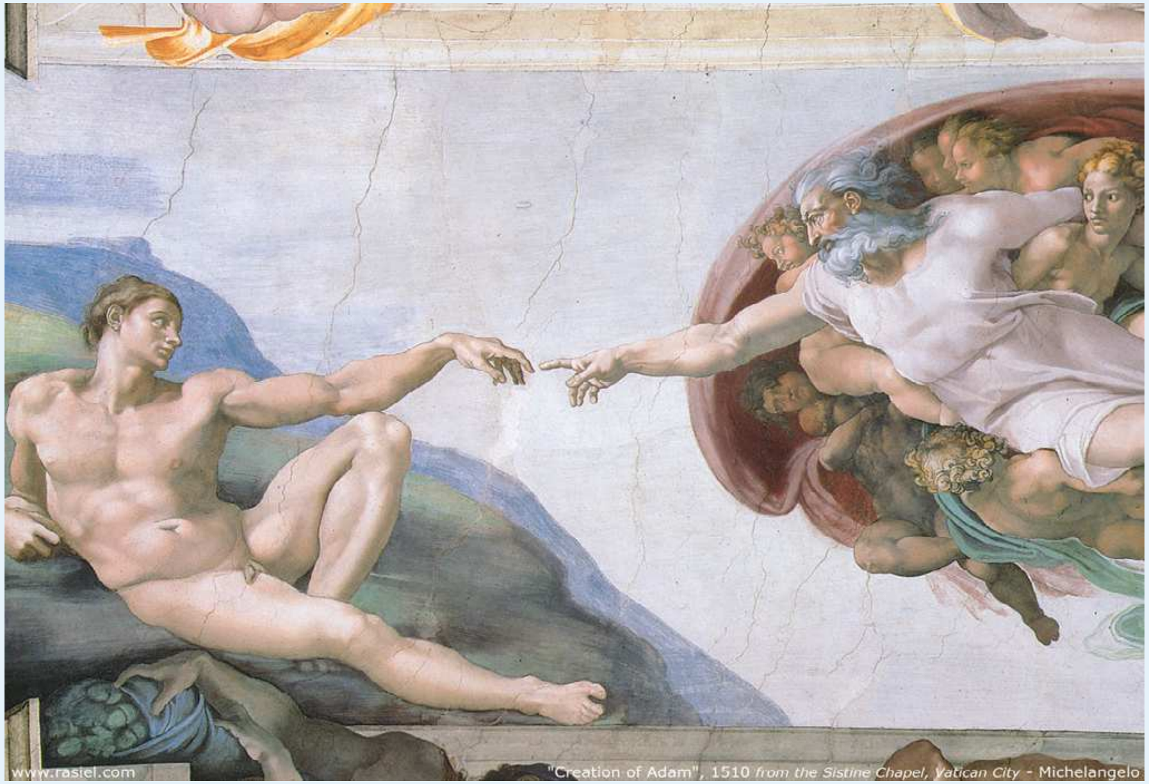
A new Clue to explain Existence?



Alexander Lenz

IPPP Durham

A new Clue to explain Existence I

- 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 II

- 1005.2757 D0 (submitted Sunday, 16.5.2010) 236 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.

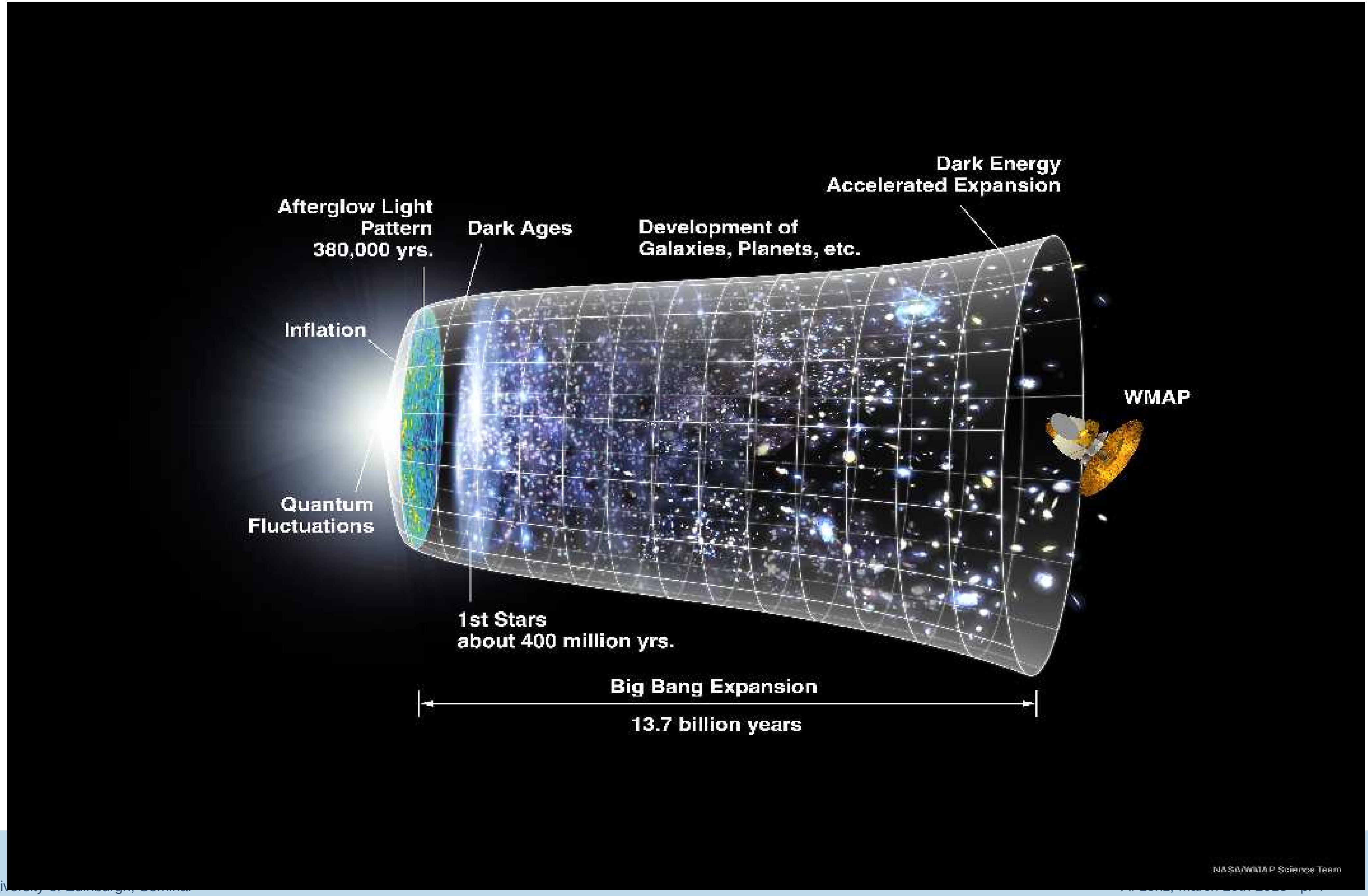
DOI: 10.1103/PhysRevD.82.032001 PACS numbers: 13.25.Hw, 11.30.Er, 14.40.Nd

[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 I



Motivation II - 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?

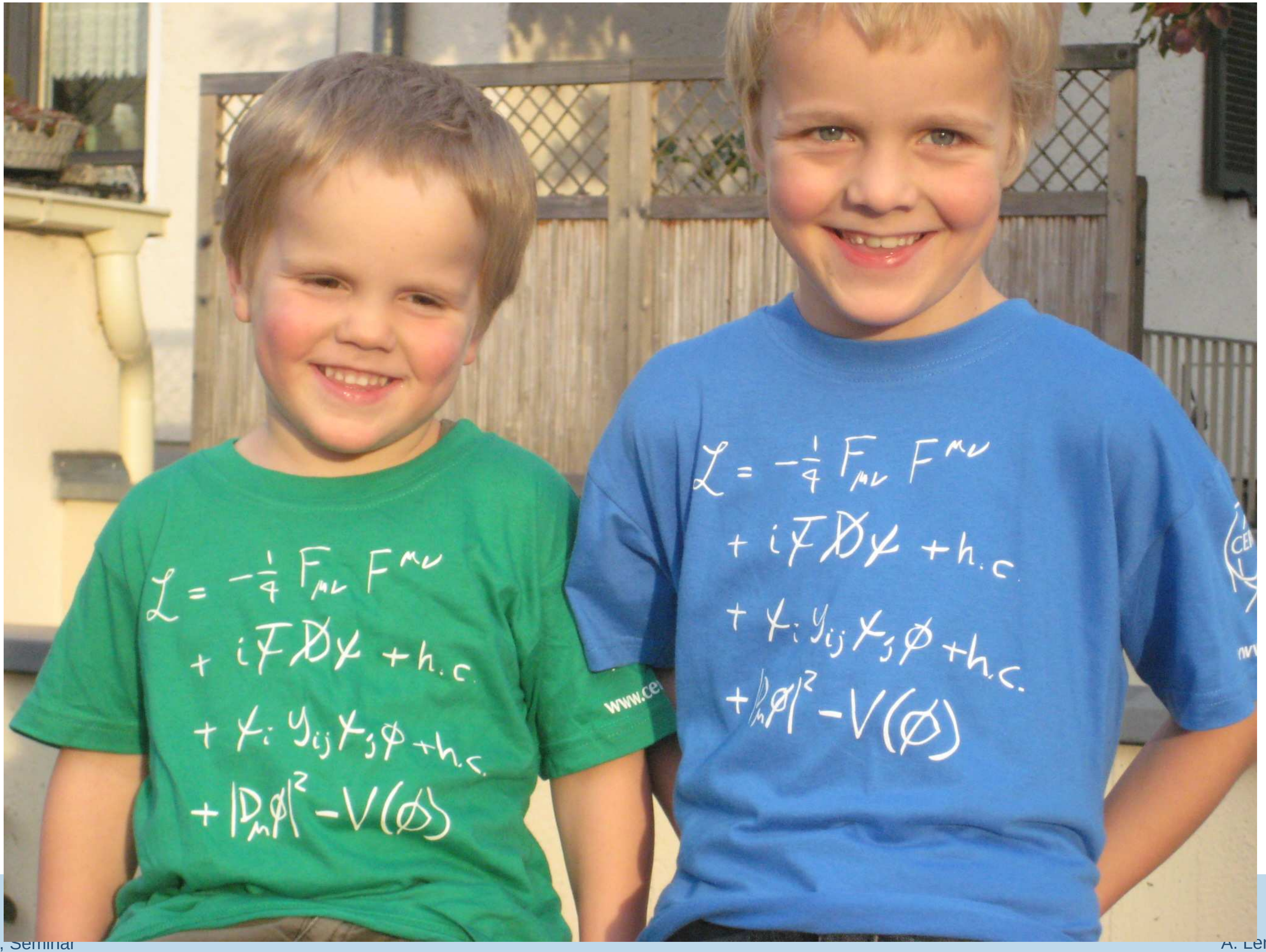
1967 Sakharov: The fundamental laws of nature must have several properties, in particular

CP-violation: 1964 Kaons (NP ’80); 2000 B-Mesons; 2011 Charm

Can our fundamental theory cope with these requirements?

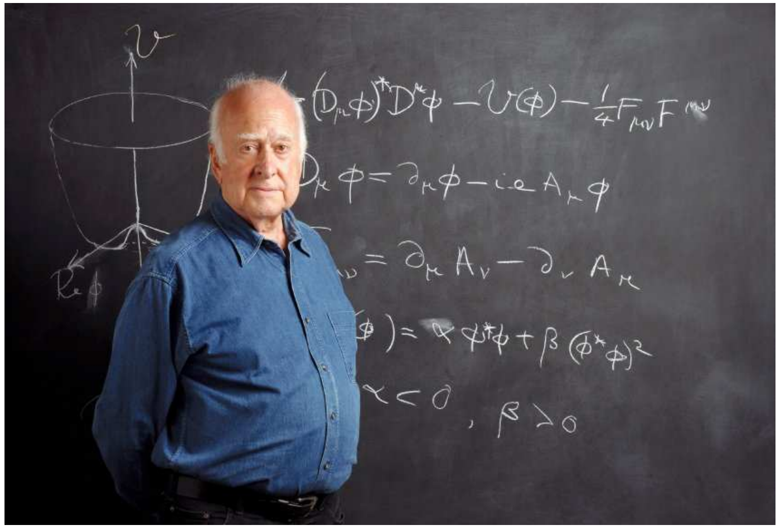
Motivation III - Our fundamental Theory

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



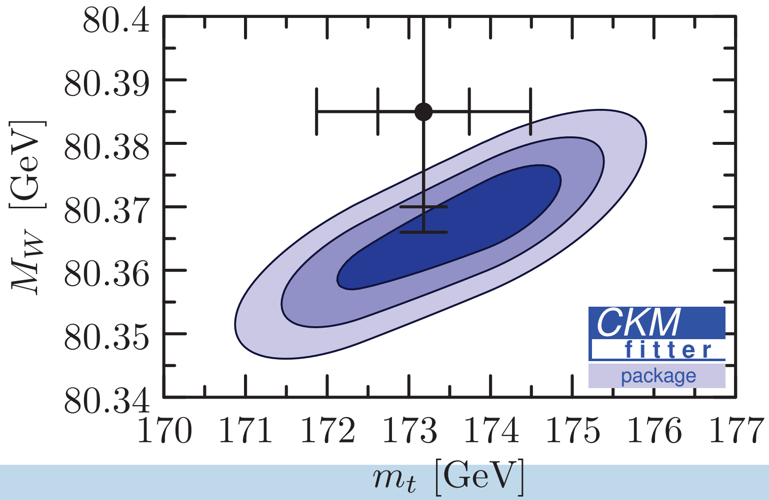
Motivation IV - Our fundamental Theory

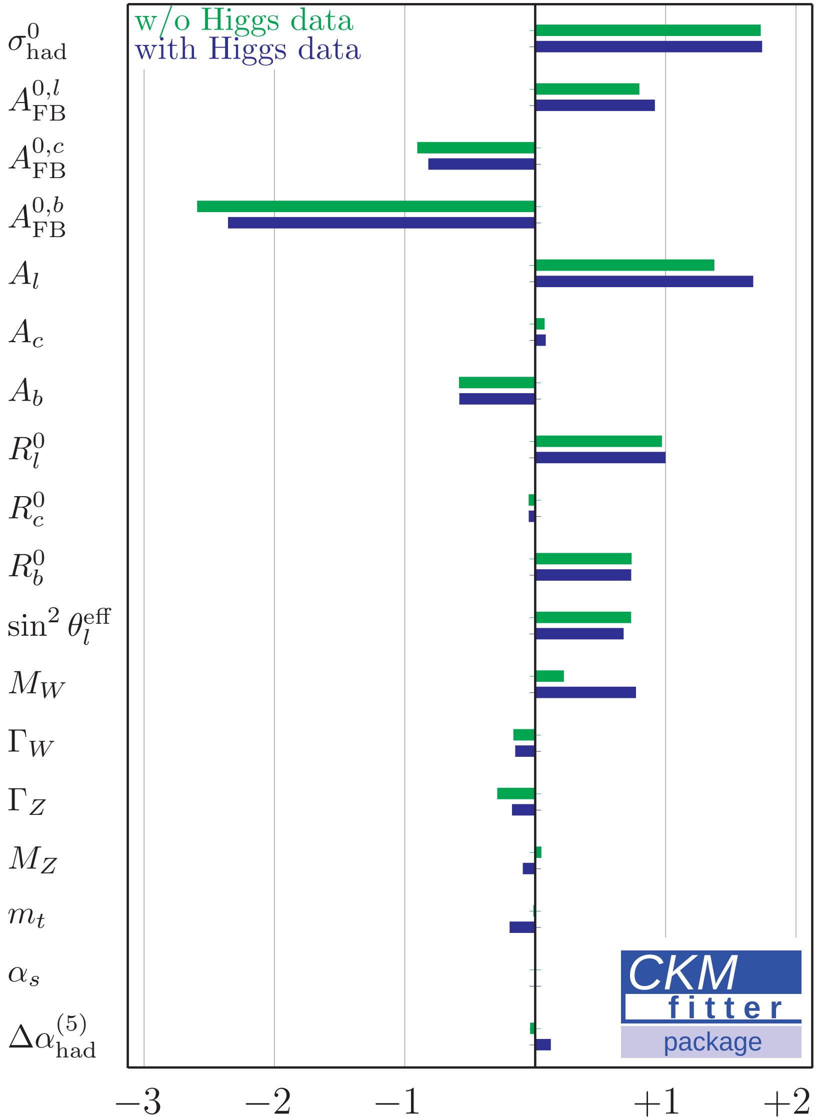
SM seems to be complete now - first electro-weak fit



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

see also **GFitter 1209.2716**



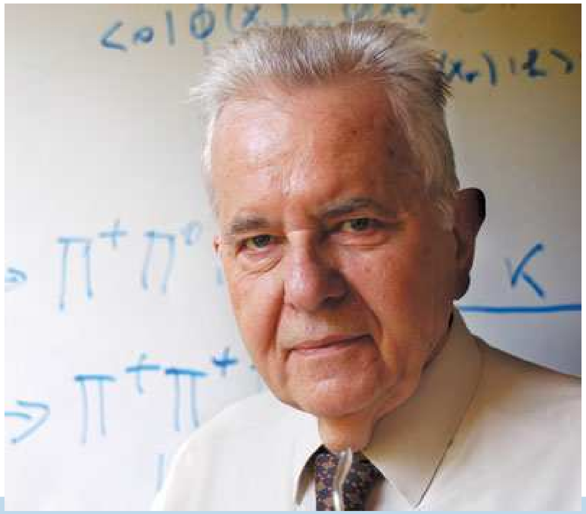


Implementation of CP violation in the CKM matrix - need at least 3 families

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

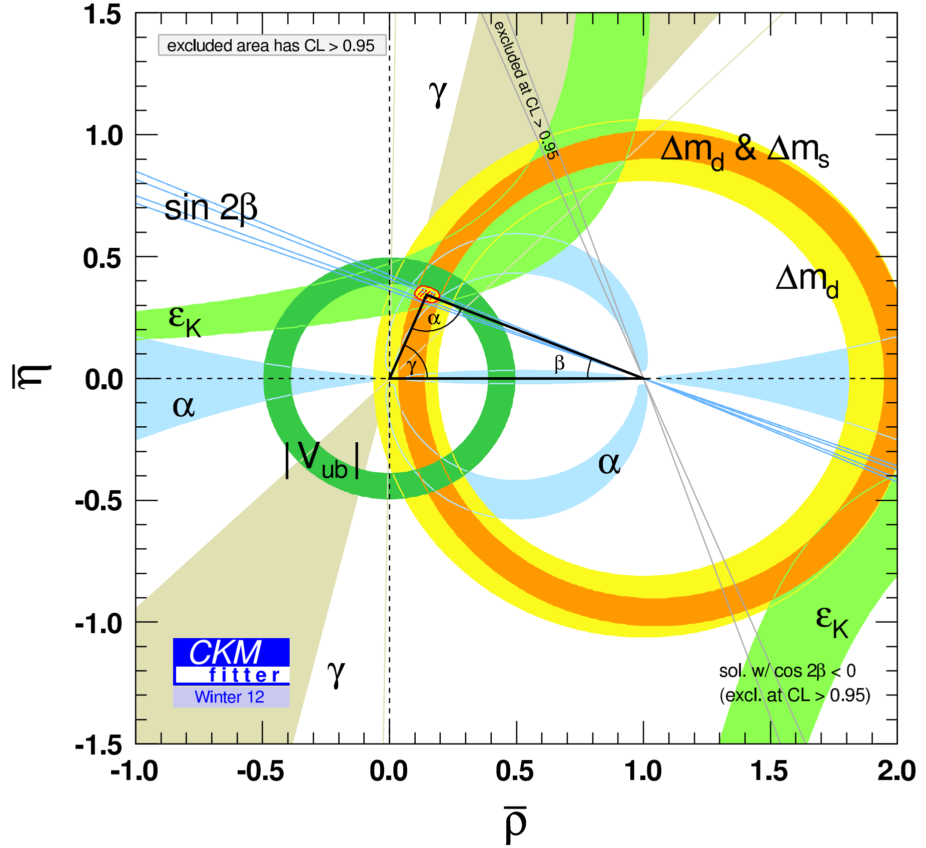
$$V_{CKM} = \begin{pmatrix} 0.97425^{+0.00022}_{-0.00014} & 0.22543^{+0.00059}_{-0.00095} & 0.00355^{+0.00015}_{-0.00012} \\ 0.22529^{+0.00060}_{-0.00094} & 0.97342^{+0.00022}_{-0.00015} & 0.04126^{+0.00060}_{-0.00104} \\ 0.00857^{+0.00033}_{-0.00030} & 0.04051^{+0.00060}_{-0.00104} & 0.999142^{+0.000043}_{-0.000025} \end{pmatrix}$$

Fit from **CKMfitter 2012**, see also **UTfit ...**



NP 2008

Motivation VI - CKM works perfect



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

But amount of CP violation seems to be too small

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

Better look in the lepton sector?

Outline

- Traditional Motivation for Flavour Physics - done
- Flavour Physics: State of the Art and Motivation
- Highlights
  - Test of our theoretical Understanding
  - Search for New Physics (NP)
  - The second Charm Revolution
- The Road to follow
  - Test of our theoretical Understanding
  - Search for New Physics (NP)
  - Explore the Charm Sector
- Conclusion

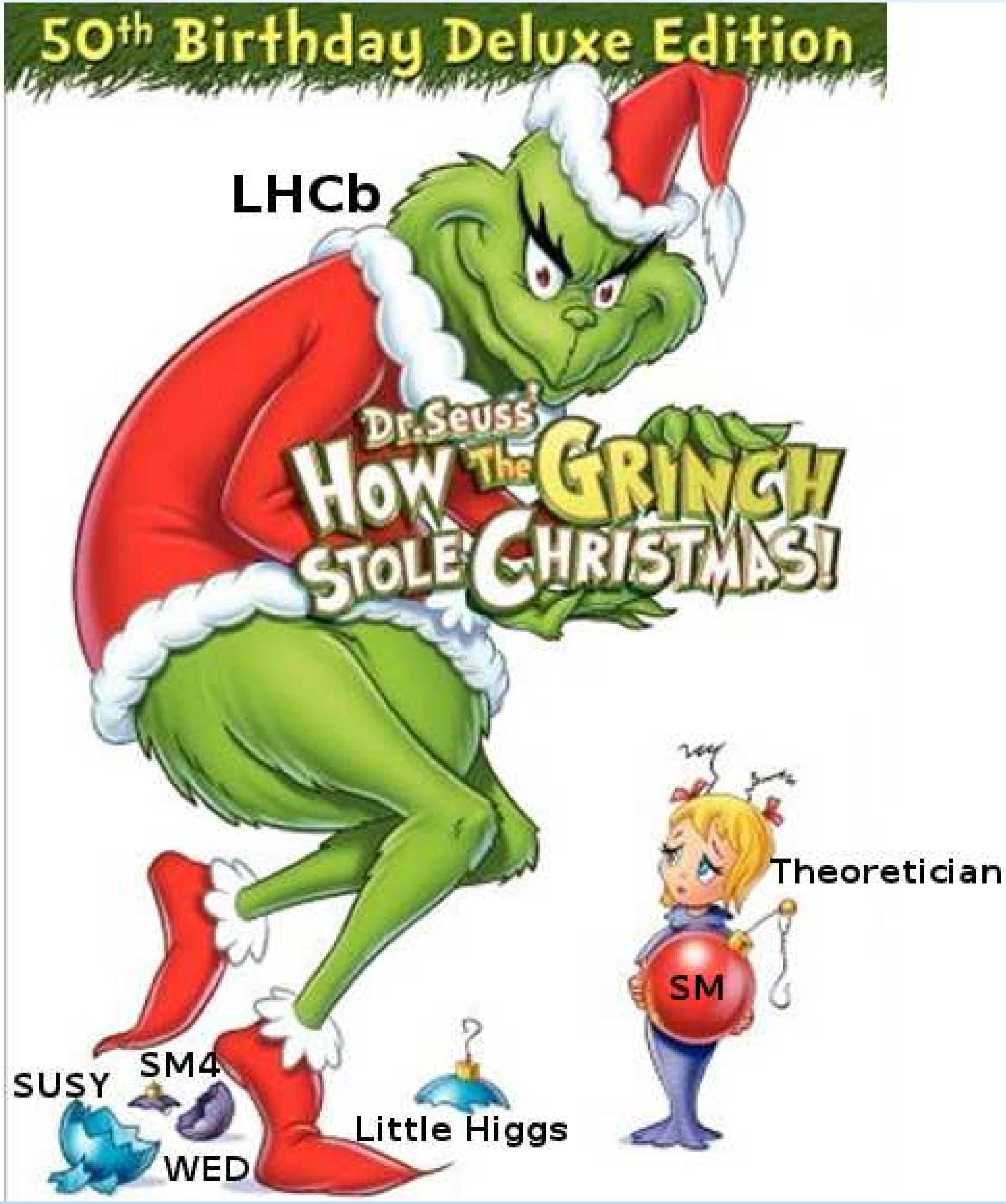
Flavour Physics: Status before LHC

- 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 new physics in B-mixing: Di-muon asymmetry; $B_s \to J/\psi\phi$...
  - Problems with $\sin 2\beta$ - V_{ub} - $B \to \tau\nu$
  - CDF has hints for a large $B_s \to \mu\mu$ branching ratio

- Motivation for Flavour Physics (personal ranking)
  1. Evidence for missing CP violation in B physics observables
  2. Discover NP via deviations of experiment from SM
  3. Determine NP parameters, if NP has been found directly
  4. Determine SM parameters as precise as possible
  5. Test of our theoretical tools

Status in 03/13: We expected a lot, and then...



Status in 03/13: 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

  - Some discrepancies remain, e.g. $B \to D^{(*)}\tau\nu$, ...
  - Some very interesting results in the Charm sector

- Motivation for Flavour Physics (personal ranking)
  1. Constrain NP models
  2. High precision needed $\Rightarrow$ SM parameters - Test theoretical tools
  3. ???Evidence for missing CP violation in charm observables???
  4. Evidence for missing CP violation in B physics observables
  5. Discover NP via deviations of Experiment from SM

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

- 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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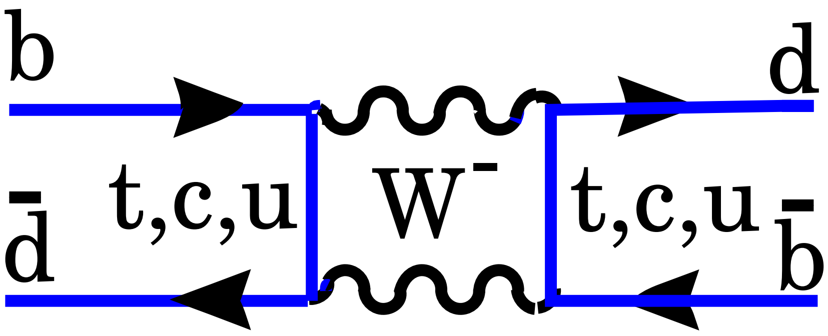
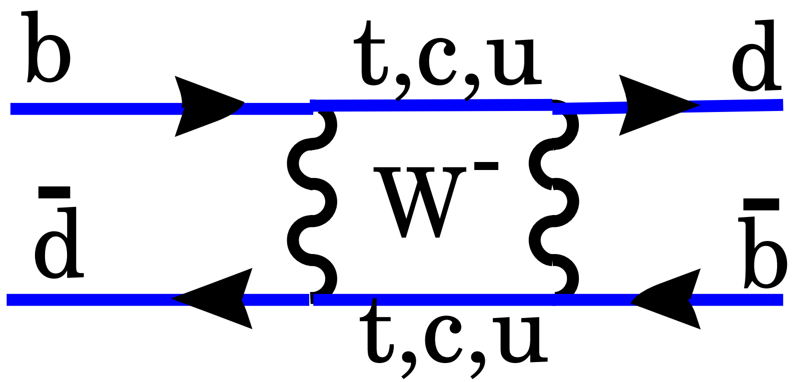
Test of our theoretical Understanding I





$|M_{12}|$, $|\Gamma_{12}|$ 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*)

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

Test of our theoretical Understanding II

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

  Theory **A.L., Nierste 1102.4274** vs. Experiment : **HFAG 12**

  $$\Delta M_d = 0.543 \pm 0.091 \text{ ps}^{-1} \qquad \Delta M_d = 0.507 \pm 0.004 \text{ ps}^{-1}$$
  $$\Delta M_s = 17.30 \pm 2.6 \text{ ps}^{-1} \qquad \Delta M_s = 17.719 \pm 0.043 \text{ ps}^{-1}$$

  - 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)

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

'98: Beneke, Buchalla, Greub, A.L., Nierste; '03: Beneke, Buchalla, A.L., Nierste;
'03: Ciuchini, Franco, Lubicz, Mescia, Tarantino; '07 Badin, Gabianni,Petrov
'06; '10: A.L., Nierste

Test of our theoretical Understanding III

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 $n_c^{\mathrm{Exp.}} < n_c^{\mathrm{SM}}$, semi leptonic branching ratio
- Mid 90's: Λ_b lifetime is too short
- before 2003: $\tau_{B_s}/\tau_{B_d} \approx 0.94 \neq 1$
- 2010/2011: Di-muon asymmetry too large

Theory arguments for HQE

$\Rightarrow$ calculate corrections in all possible “directions”, to test convergence

$\Rightarrow$ test reliability of HQE via lifetimes (no NP effects expected)

Test of our theoretical Understanding IV

(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 in prep.**
- HFAG ’03 $\tau_{\Lambda_b} = 1.229 \pm 0.080$ ps^{-1} $\longrightarrow$ HFAG ’12 $\tau_{\Lambda_b} = 1.426 \pm 0.024$ ps^{-1}
  Shift by 2.5σ!; (ATLAS: 1.45 ± 0.04 ps/CMS: 1.50 ± 0.06 ps Waiting for LHCb!)
- **HFAG 2013:** $\tau_{B_s}/\tau_{B_d} = 0.989 \pm 0.008$
- 2010/2011: Di-muon asymmetry too large — Test Γ_{12} with $\Delta\Gamma_s$!

Theory arguments for HQE

$\Rightarrow$ calculate corrections in all possible “directions”, to test convergence

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

$\Rightarrow$ 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

Test of our theoretical Understanding V

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

LHCb Moriond 2012, 2013; ATLAS; CDF; DO

$$\boxed{\begin{aligned} \Delta\Gamma_s^{\mathrm{Exp}} &= (0.089 \pm 0.012)\,\mathrm{ps}^{-1} \\ \Delta\Gamma_s^{\mathrm{SM}} &= (0.087 \pm 0.021)\,\mathrm{ps}^{-1} \end{aligned}}$$

HFAG 2013

A.L.,Nierste 1102.4274

Cancellation of non-perturbative uncertainties in ratios

$$\boxed{\left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^{\mathrm{Exp}} / \left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^{\mathrm{SM}} = 1.00 \pm 0.13 \pm 0.20}$$

Dominant uncertainty = NNLO-QCD + Lattice

Test of our theoretical Understanding VI

Most important lesson?: HQE works also for Γ_{12}!

- despite small energy release $M_{B_s} - 2M_{D_s} \approx 1.4$ GeV
- Theoreticians were fighting for 35 years whether there is a violation of quark hadron duality

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

Still more accurate data needed!

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

1. Apply HQE to quantities that are sensitive to NP
2. Apply HQE to quantities in the charm system?

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Search for New Physics in B-Mixing I

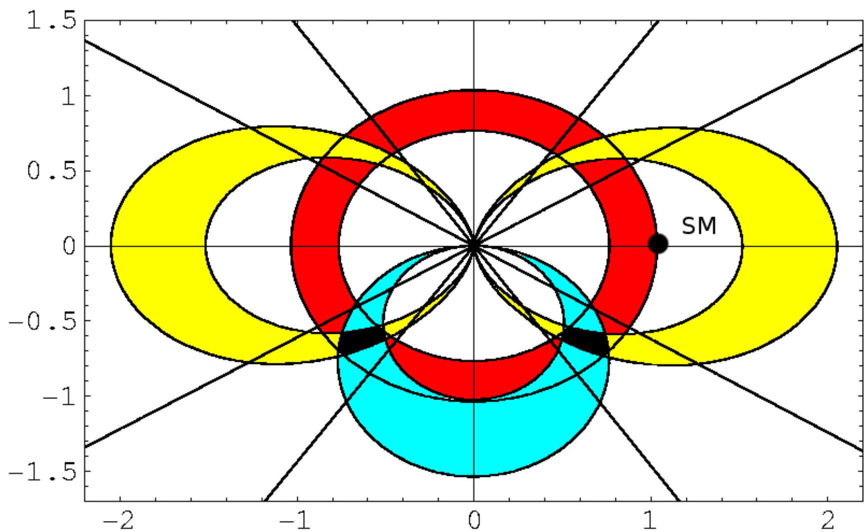
A.L., Nierste, '06

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

$$\begin{aligned}
\Delta M_s &= 2|M_{12,s}^{\rm SM}| \cdot |\Delta_s| \\
\Delta\Gamma_s &= 2|\Gamma_{12,s}| \cdot \cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right) \\
\frac{\Delta\Gamma_s}{\Delta M_s} &= \frac{|\Gamma_{12,s}|}{|M_{12,s}^{\rm SM}|} \cdot \frac{\cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)}{|\Delta_s|} \\
a_{fs}^s &= \frac{|\Gamma_{12,s}|}{|M_{12,s}^{\rm SM}|} \cdot \frac{\sin\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)}{|\Delta_s|}
\end{aligned}$$

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

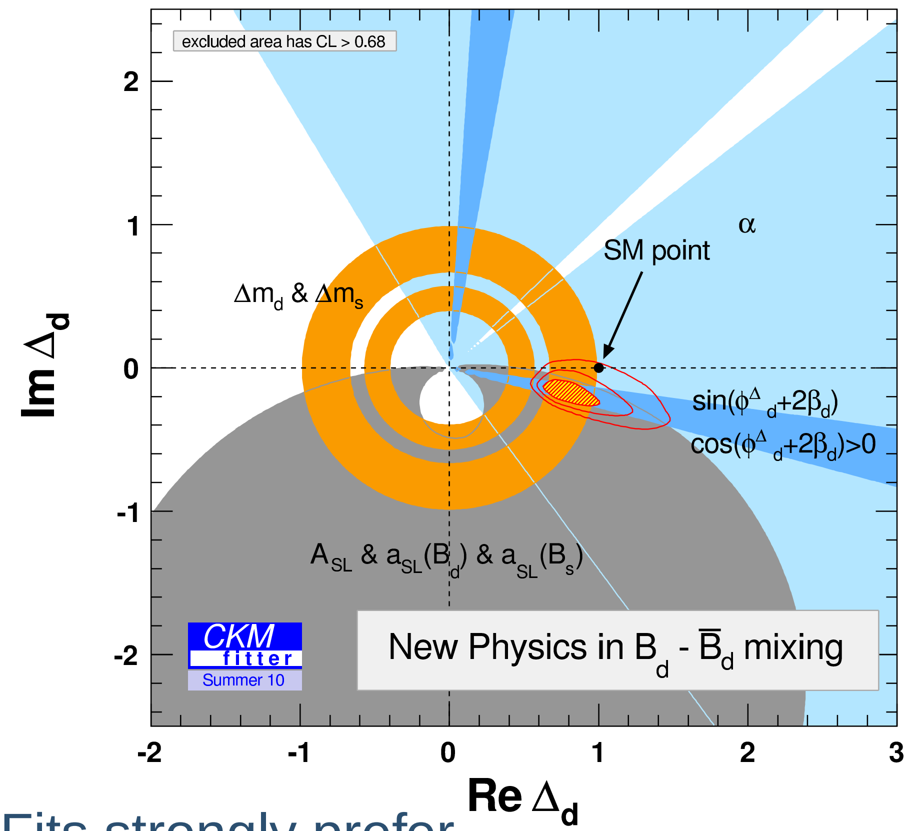
For $|\Delta_s| = 0.9$ and $\phi_s^\Delta = -\pi/4$ one gets the following bounds in the **complex Δ-plane**:

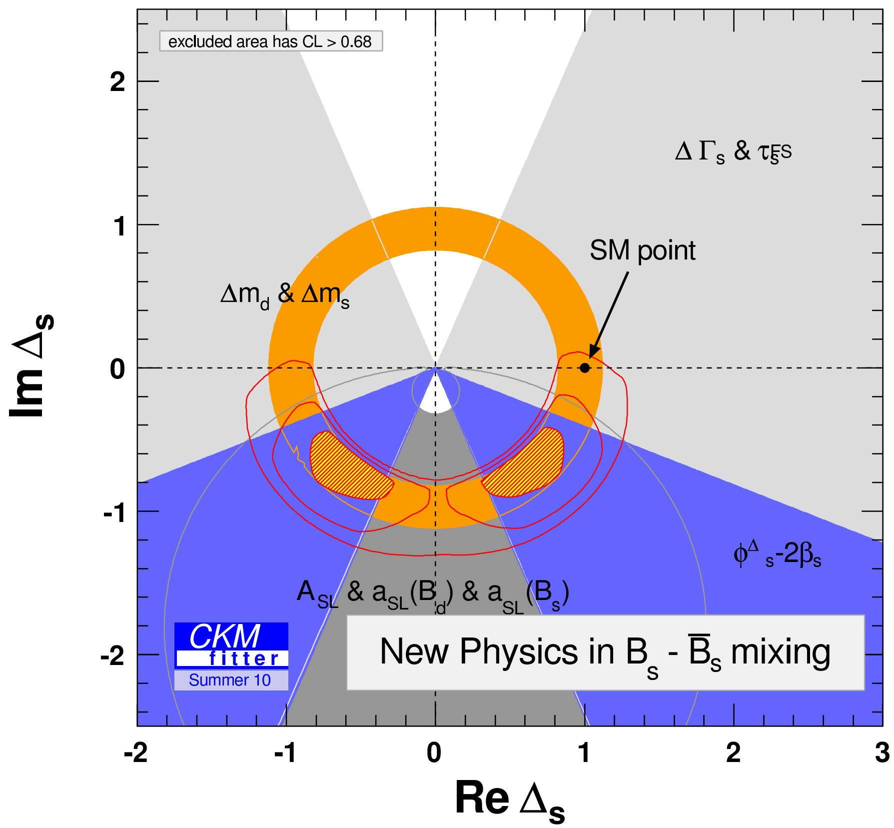


Search for New Physics in B-Mixing II

Combine all data before summer 2010 and neglect penguins

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





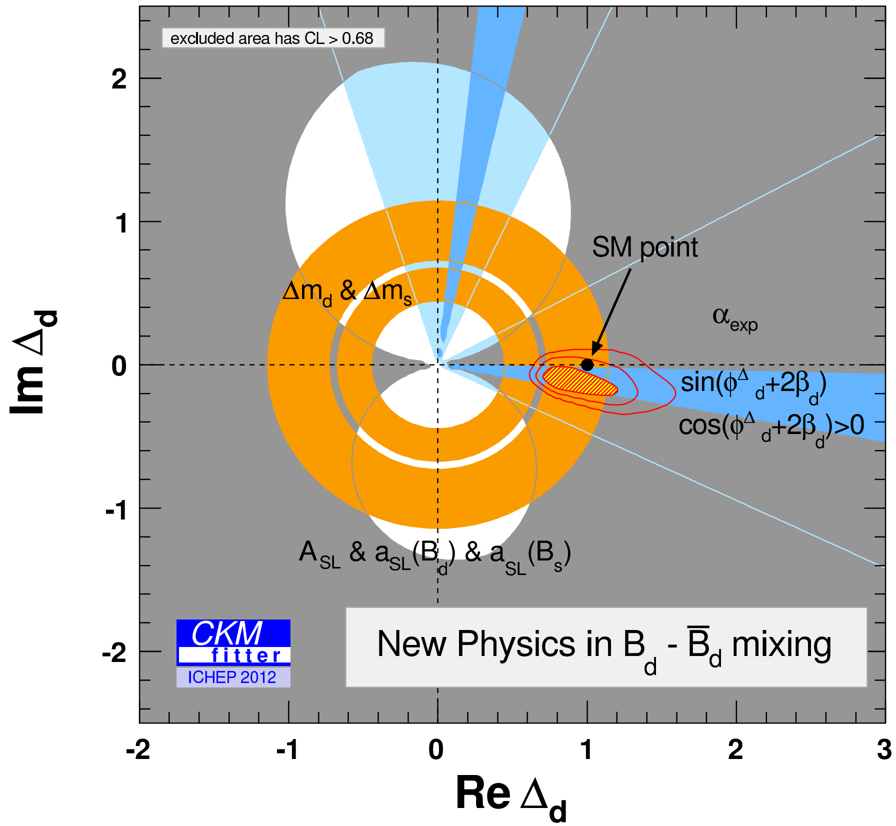
Fits strongly prefer

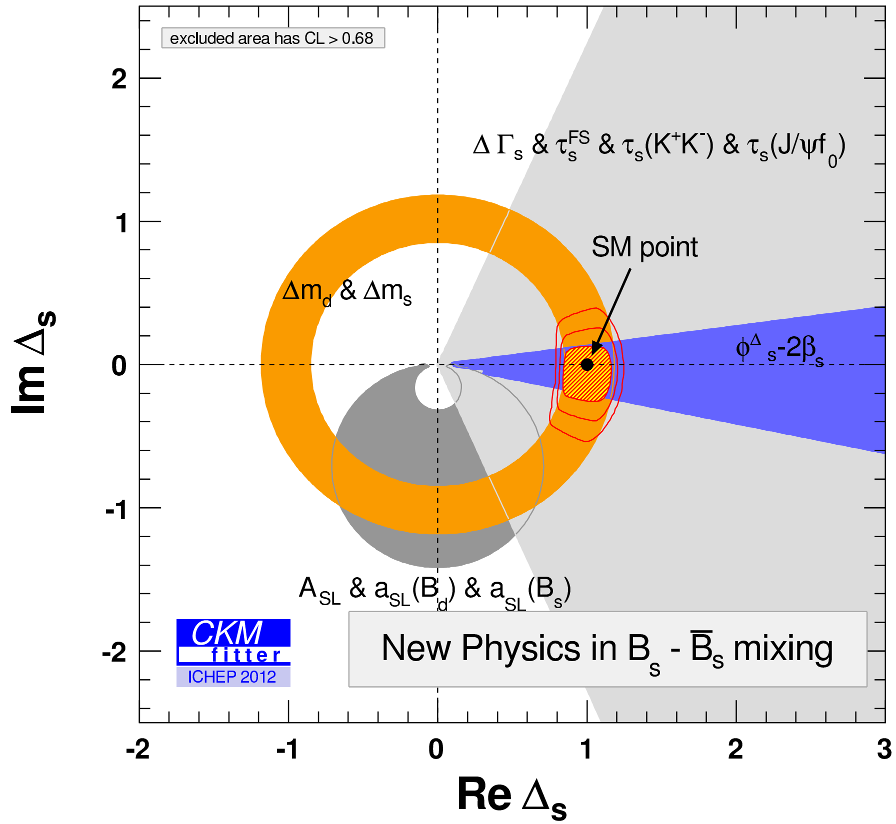
- **large new physics effects in the B_s-system**
- **some new physics effects in the B_d-system**

Search for New Physics in B-Mixing III

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 IV: 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 $\tau_{B_s}/\tau_{B_d}, n_c, \ldots$
   But still some sizable NP possible - investigate e.g. n_c
   Bobeth, Haisch 1109.1826
3. Look at experimental side
   - Statistical fluctuation - **soon update from D0**
   - 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 less than 3σ

A_{sl}^b: **less promising candidate for *the Clue* - look also somewhere else**

Search for NP in B-Mixing V: $a_{sl}^{d,s}$

Recently new measurements for the individual semi leptonic CP asymmetries were made public

$$a_{sl}^{s} = -0.24 \pm 0.54 \pm 0.33\%$$ **LHCB-CONF-2012-022**

$$a_{sl}^{s} = -1.08 \pm 0.72 \pm 0.17\%$$ **D0 1207.1769**

$$a_{sl}^{d} = 0.68 \pm 0.45 \pm 0.14\%$$ **D0 1208.5813**

$$a_{sl}^{d} = 0.06 + 0.39 - 0.36\%$$ **BaBar 1301.4166 CKM2012**

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

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The second CHARM Revolution I

- D-mixing rate is large (HFAG 2012)

$$\frac{\Delta M}{\Gamma} = 0.63^{+0.19}_{-0.20}\% \qquad \frac{\Delta\Gamma}{2\Gamma} = 0.75 \pm 0.12\%$$

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

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

$$\Delta A_{CP}^{dir} = -0.656 \pm 0.154\%$$

LHCb; CDF; Belle

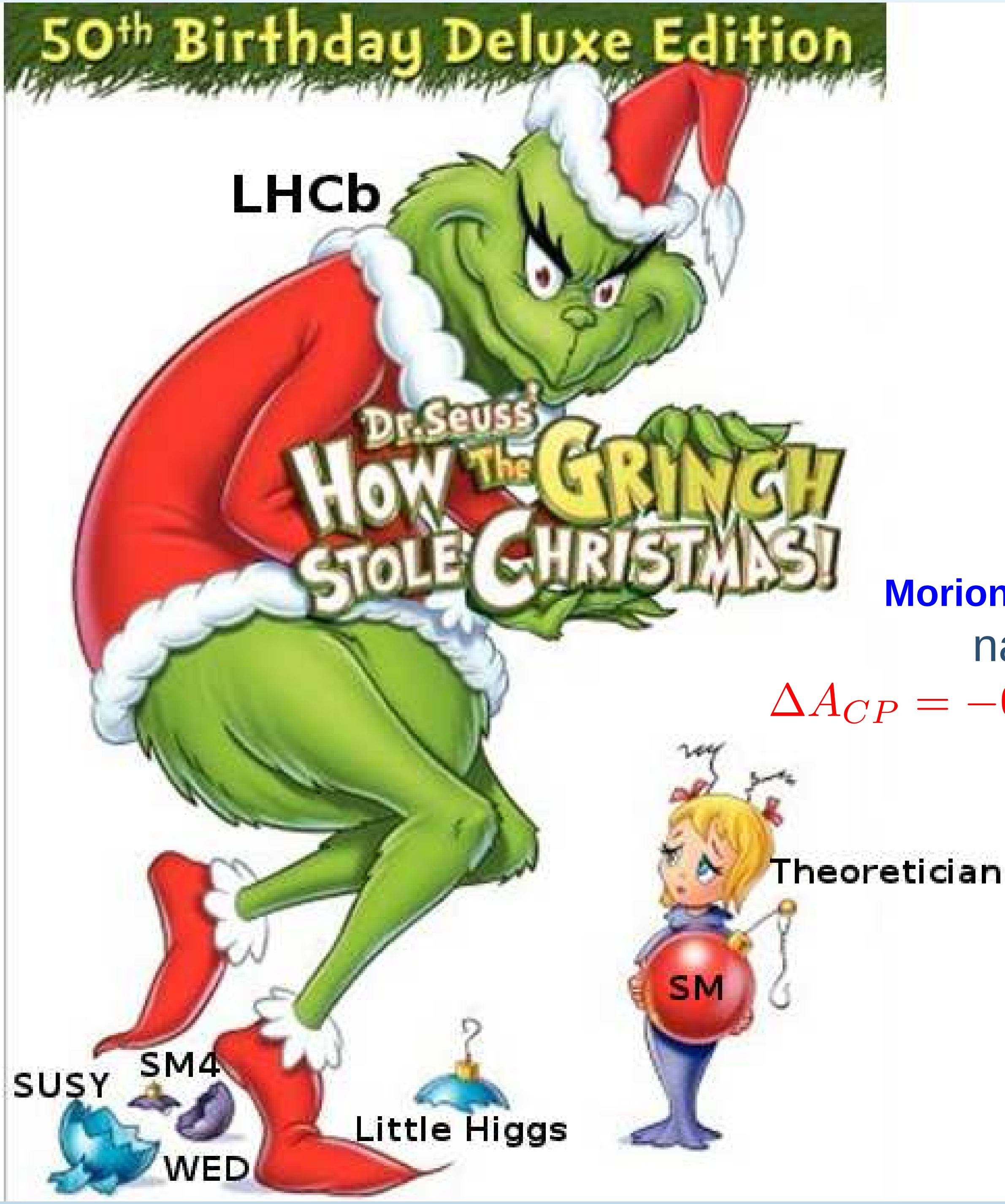
The crucial question: Can this be described within the SM or is it NP?

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

$$\begin{aligned} m_{B_s} - 2m_{D_s} &\approx 1.43 \text{ GeV} \\ m_D - 2m_K &\approx 0.9 \text{ GeV} \\ m_D - 2m_\pi &\approx 1.6 \text{ GeV} \end{aligned}$$

Let’s try!

LHCb now also kills its own hints...



Moriond 2013/CERN:
naive average
$\Delta A_{CP} = -0.15 \pm 0.16\%$

The second CHARM Revolution II

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

The second CHARM Revolution III

- ’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 **Bobrowski, A.L., Rauh; 1208.6438**

$$\boxed{\frac{\tau(D+)}{\tau(D^0)} = 2.8 \pm 1.5(\text{hadronic ME})^{+0.3}_{-0.7}(\text{scale}) \pm 0.2(\text{parametric})}$$

- 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

The road to follow - What to do?

1. **CKM mechanism works perfectly**
   - Our theoretical tools have passed many non-trivial cross-checks

$$\Delta\Gamma_s^{\mathrm{SM}} = \Delta\Gamma_s^{\mathrm{Exp.}}$$

2. **Missing CPV for the origin of matter in the universe still not identified**
   - Still some room for new effects - look for new extraction strategies
   - Some remaining discrepancies - e.g. A_{sl} (now $< 3\sigma$), $B \to D\tau\nu$,...
   - Combine flavour bounds on NP models with e.g. Higgs-, Lepton-,...bounds

3. **There are many new, exciting results for the charm-system – CP violation!**
   - Understand the SM background

4. **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,...)

The road to follow

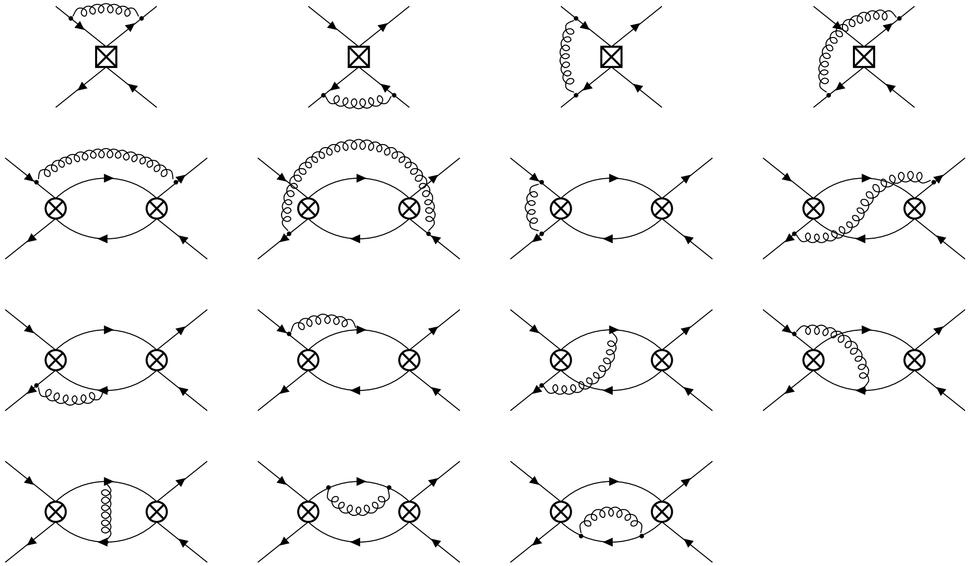
- Test of our theoretical Understanding
  - b-hadron lifetimes
  - More precise determination of Γ_{12}
  - Penguin contributions
- Search for New Physics (NP)
  - Model independent search with inclusive decays - includes $B_s \to \tau\tau$
  - (2HDM)
- (Explore the Charm Sector)
  - Lifetimes
  - Mixing

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

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

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

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



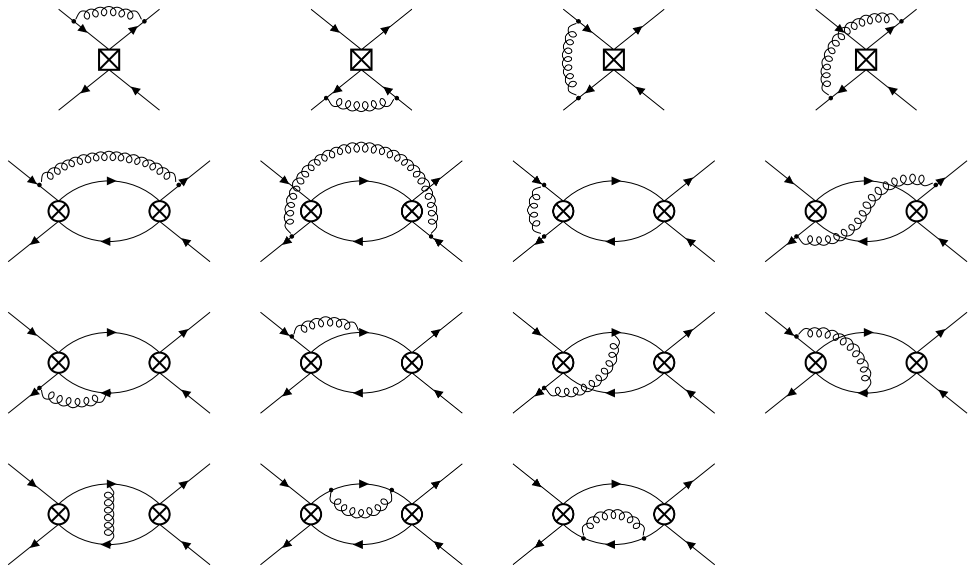
$$\left[\frac{\tau(B^+)}{\tau(B_d^0)}\right]_{\mathrm{LO,NLO,HFAG10}} = 1.047 \pm 0.049 \leftrightarrow 1.063 \pm 0.027 \leftrightarrow 1.071 \pm 0.009$$

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

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

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

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



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

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

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

with non-perturbative input from **Becirevic hep-ph/0110124**

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

Update urgently needed!

Lifetimes: Lifetimes of heavy hadrons

- $\tau(B^+)/\tau(B_d)$: seems ok, **but more precise hadronic ME urgently needed**
- $\tau(B_s)/\tau(B_d)$:

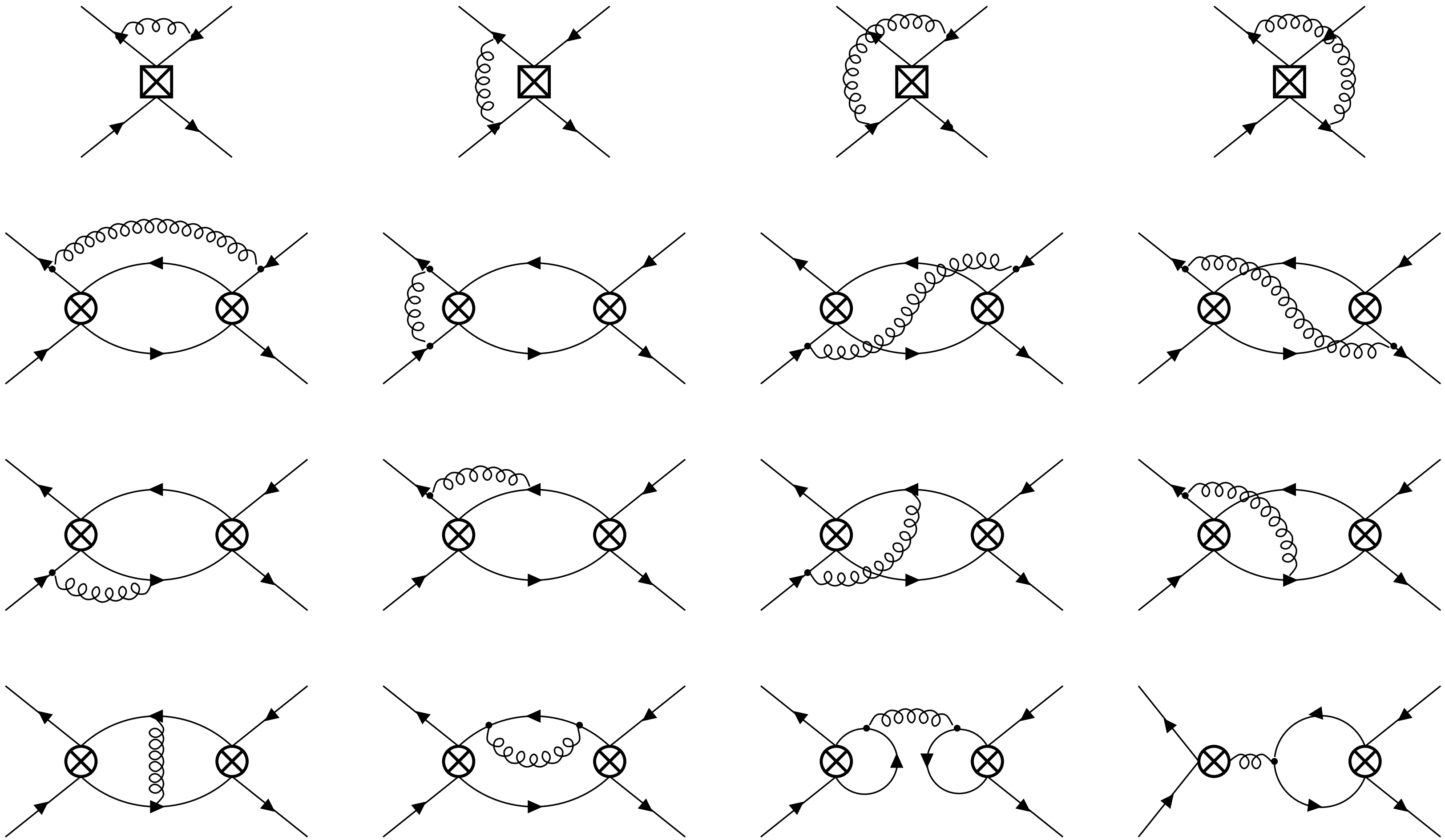
$$\tau_{B_s}^{\text{Exp}} = \begin{cases} 1.477 \pm 0.018\,\text{ps} & \text{ATLAS} \\ 1.520 \pm 0.020\,\text{ps} & \text{LHCb} \\ 1.528 \pm 0.021\,\text{ps} & \text{CDF} \\ 1.443 \pm 0.037\,\text{ps} & \text{D0} \end{cases} \qquad \tau_{B_s}^{\text{SM}} = (0.996...1.000) \cdot (1.519 \pm 0.007)\text{ps}$$

  More data as well as non-perturbative matrix elements needed

- $\tau(\Lambda_b)$, $\tau(\Xi_b)$ and $\tau(B_c)$: more data and further theory work (perturbative and non-perturbative) necessary
- $\tau(D)$: work in progress
  It is not unplausible that HQE might give reasonable estimates
  hadronic matrix elements mandatory!

Theory Prediction for $\Delta\Gamma_s$

Calculating the following diagrams



Theory Prediction for $\Delta\Gamma_s$

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!

Theory Prediction for $\Delta\Gamma_s$

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

Theory Prediction for $\Delta\Gamma_s$

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%

Theory Prediction for $\Delta\Gamma_s$

The current experimental error is smaller than the theory error

In order to reduce the theoretical error in $\Delta\Gamma_s$, one needs:

- Non-perturbative estimates of the ME of the dimension 7 operators
- α_s-corrections to the Wilson coefficients of the dimension 7 operators

- Precise non-perturbative values of the ME of the dimension 7 operators
- α_s^2-corrections to the Wilson coefficients of the dimension 6 operators

How large are Penguins? I

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? II

Many observables in the B_s mixing system:

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

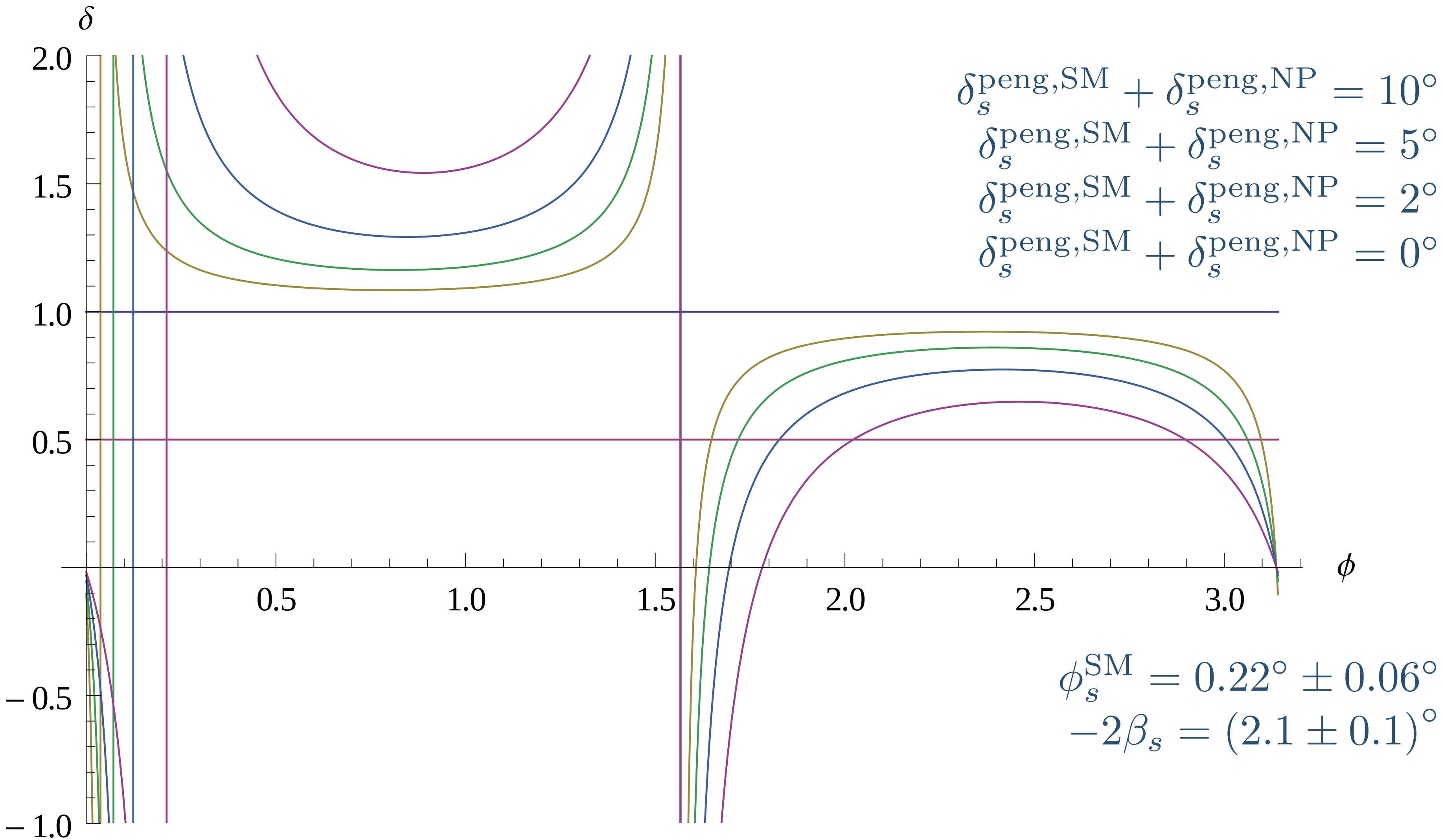
$$\boxed{a_{sl}^s = -\frac{\Delta\Gamma}{\Delta M}\frac{S_{\psi\phi}}{\sqrt{1-S_{\psi\phi^2}}}\cdot\delta}$$

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

How large are Penguins? III



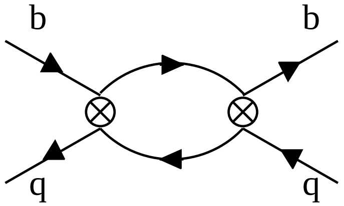
- Above relation can be used to determine $\delta_s^{\text{peng,SM}} + \delta_s^{\text{peng,NP}}$
- To extract ϕ_s^{Δ} one needs $\Gamma_{12}^{s,\text{SM}}$

A.L. 1106.3200

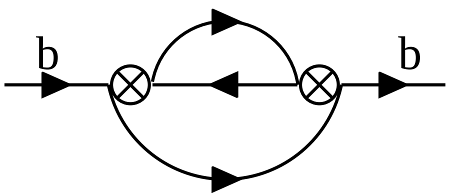
New physics in Γ_{12}?

- **Large ($\mathcal{O}(200-3400\%)$) NP effects in Γ_{12}?** **Why not seen somewhere else?**

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

  - 

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

  - 

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

  - 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 best bound $Br(B_s \to \tau\tau < 5\%)$ - LHCb should do better :-)

New physics in Γ_{12}?

- **Missing charm puzzle; semileptonic 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-decay into 0, 1, 2 c-quarks

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

  The average number of charm quarks per b-decay reads

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

Buchalla, Dunietz, Yamamoto '95

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

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

Search for New Physics

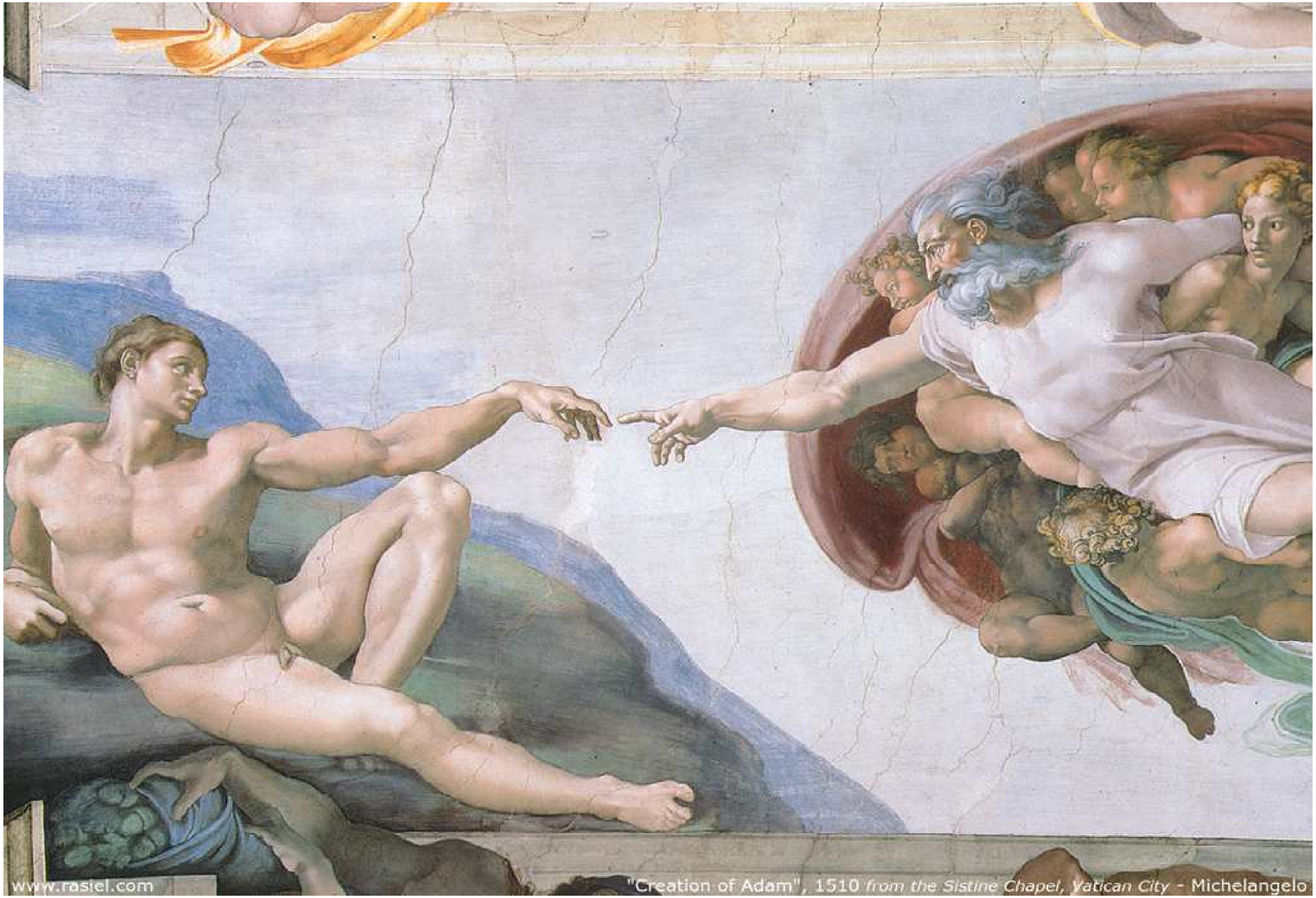
Investigation of B_{sl} and n_c gives model- and even decay channel independent constraints on NP models!

- Theory predictions:
  - NLO-QCD stems from 1994/95 **Bagan, Ball, Braun, Fiol, Gosdzinsky**
  - Literature contains several misprints (result is e.g. not IR finite)
  - Authors left physics, retired, do now Quantum computing ...
  - Recalculation with students at TU Munich finished **Krinner, Rauh**
- Experiment:
  - Latest experimental still stem from CLEO and LEP!
  - Inclusive decays are theoretically nice but experimentally very difficult
    Monte Carlo (Sherpa) investigations just started with **Frank Krauss and students**

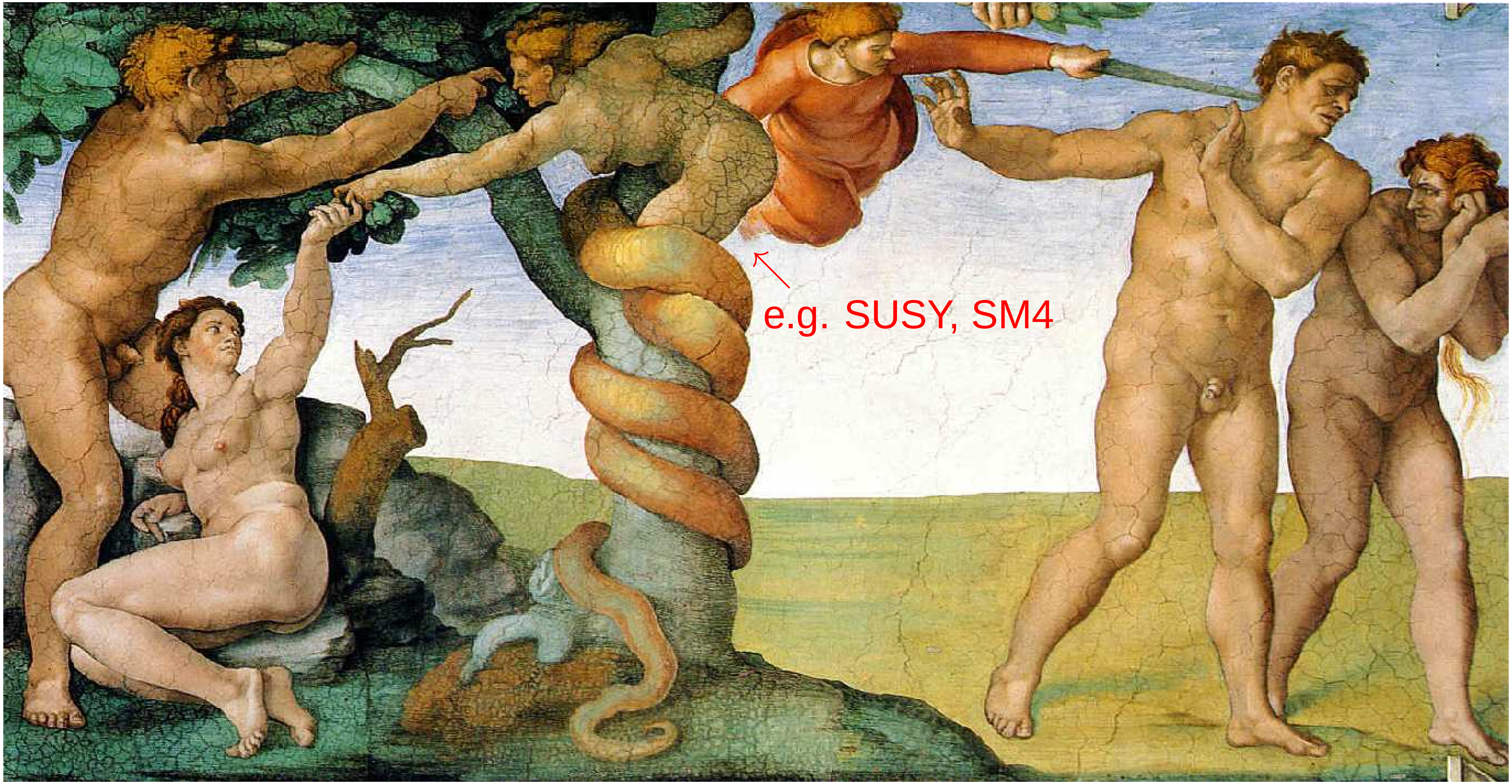
Conclusion - The road to follow

- Test of our theoretical Understanding
  - b-hadron lifetimes - Lattice, pert. QCD
  - More precise determination of Γ_{12}- Exp., Lattice, pert. QCD
  - Penguin contributions - Exp., pert. QCD
- Search for New Physics (NP)
  - Model independent search with inclusive decays - includes $B_s \to \tau\tau$ - Exp., pert. QCD, Monte Carlo
  - (2HDM)
- (Explore the Charm Sector)
  - Lifetimes
  - Mixing

FP $\equiv$ A new clue to explain existence?



BUT: FP might also kill your favourite model



UK Flavour 2013

September 4th-7th 2013 http://www.ippp.dur.ac.uk/Workshops/13/UKflavour2013/

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UK Flavour 2013

September 4th-7th 2013

The aim of this workshop is to bring together UK experts in flavour physics working in experiment, phenomenology and lattice QCD to discuss the status and prospects of the field in light of the recent experimental results from LHCb, ATLAS, CMS, BaBar and Belle. Topics include:

- Heavy b- and c- hadrons
- Exotic heavy hadrons
- b hadron lifetimes & mixing
- Rare decays I (b -> sll)
- Rare decays II (Bs -> mu mu and other RD)
- CKM fits
- Hadronic CPV
- Charm mixing and CPV
- Kaons
- Beyond SM

Note that this workshop starts immediately after the CHARM 2013 conference in Manchester.

Please note that participation is by invitation only.

Workshop website hosted by the Institute for Particle Physics Phenomenology
Edit this site