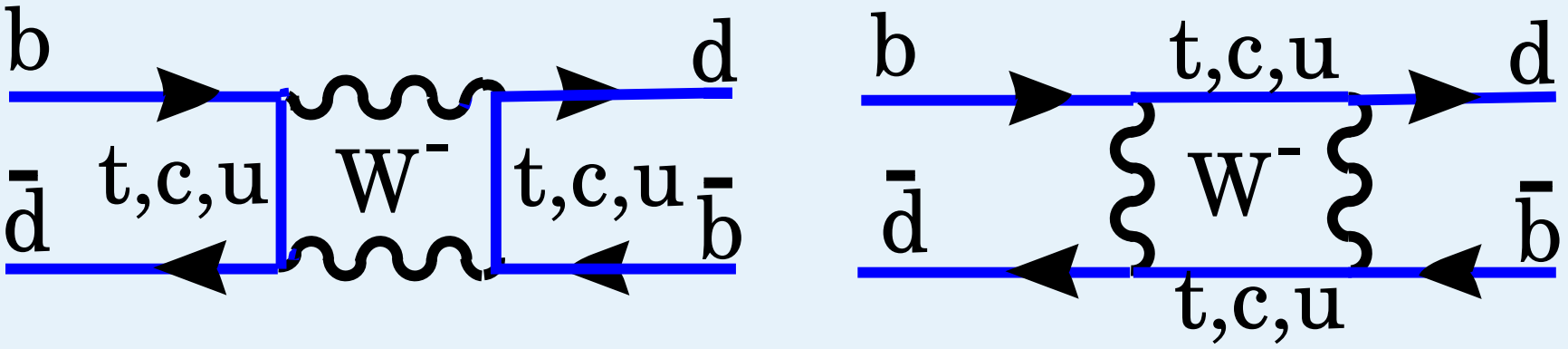
Status and Prospects of B-mixing



Alexander Lenz

CERN, Theory Division

Content

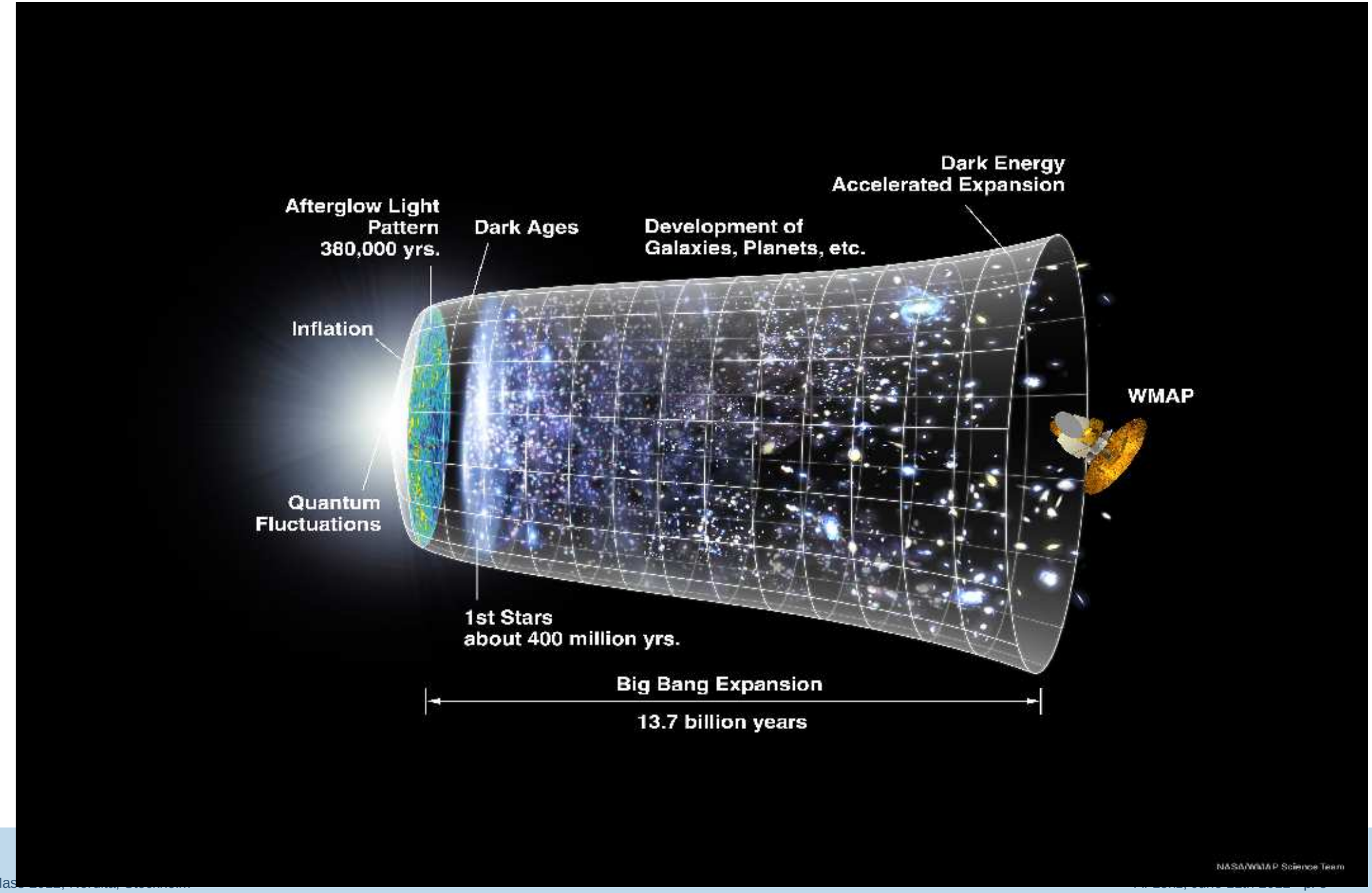
- Introduction

- CKM^{+}: The CKM paradigm is great
- CKM^{0}: The CKM paradigm might be better
- CKM^{-}: The CKM paradigm is violated by New Physics!

- Status of B-mixing after Moriond 2012

- Wish-list for Experiments

Introduction I



Introduction II - 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,...

Introduction II - Baryon Asymmetry

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

Introduction II - 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?

Introduction II - 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?

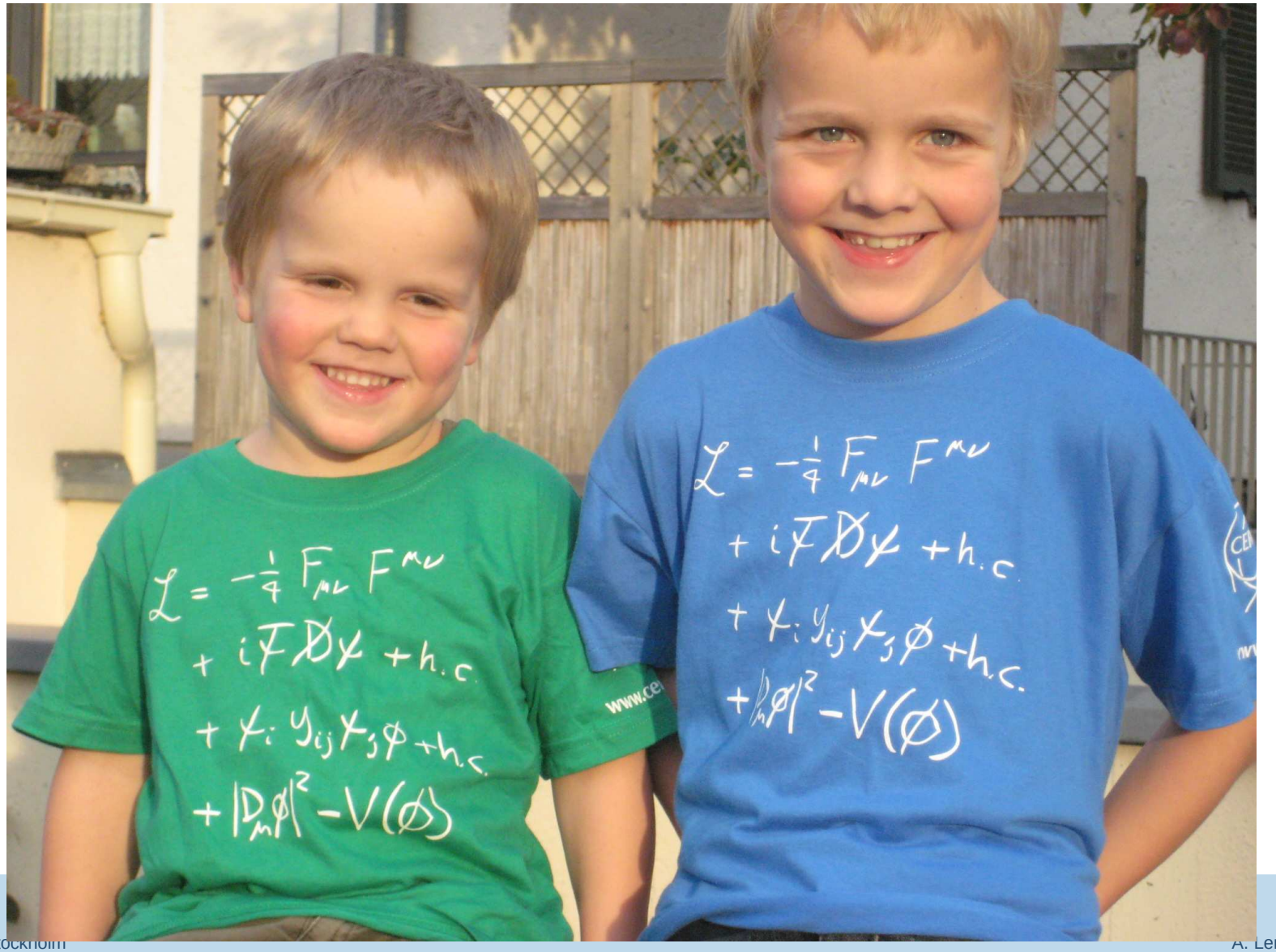
1967 Sakharov: The fundamental laws of nature must have several properties, in particular

CP-violation: 1964 K-Mesons (NP 1980) 2000 B-Mesons

Can our fundamental theory cope with these requirements?

Success of the SM I

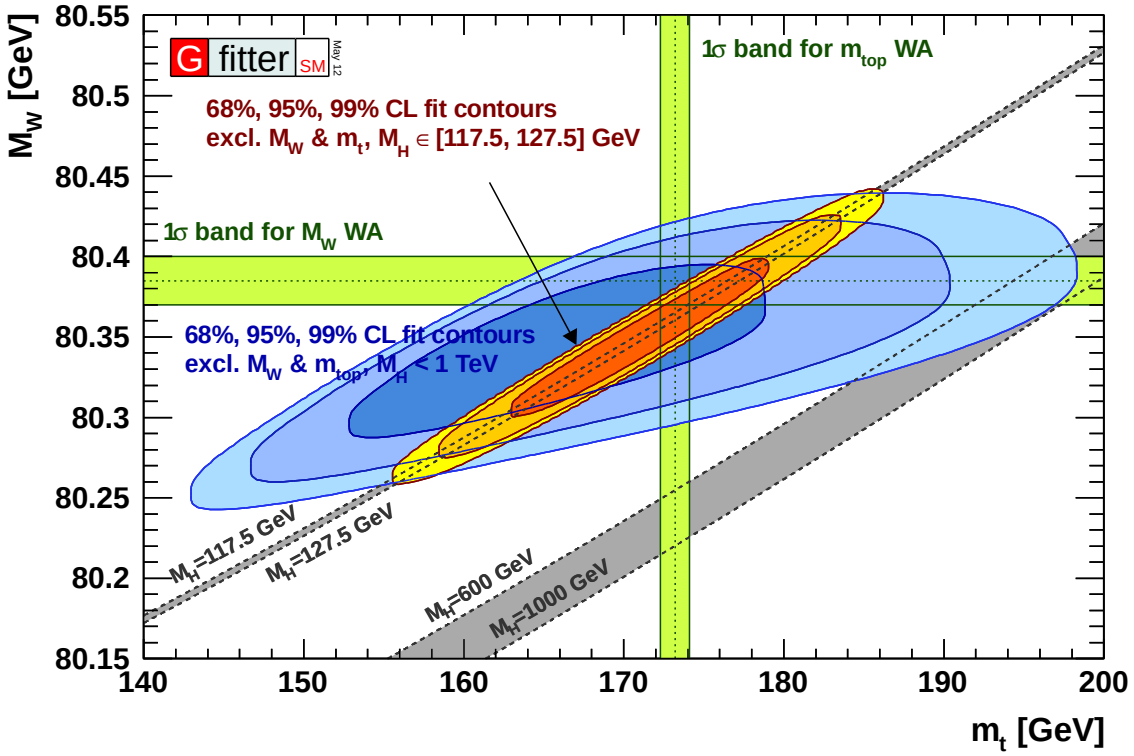
Elegant description of nature at per mille precision

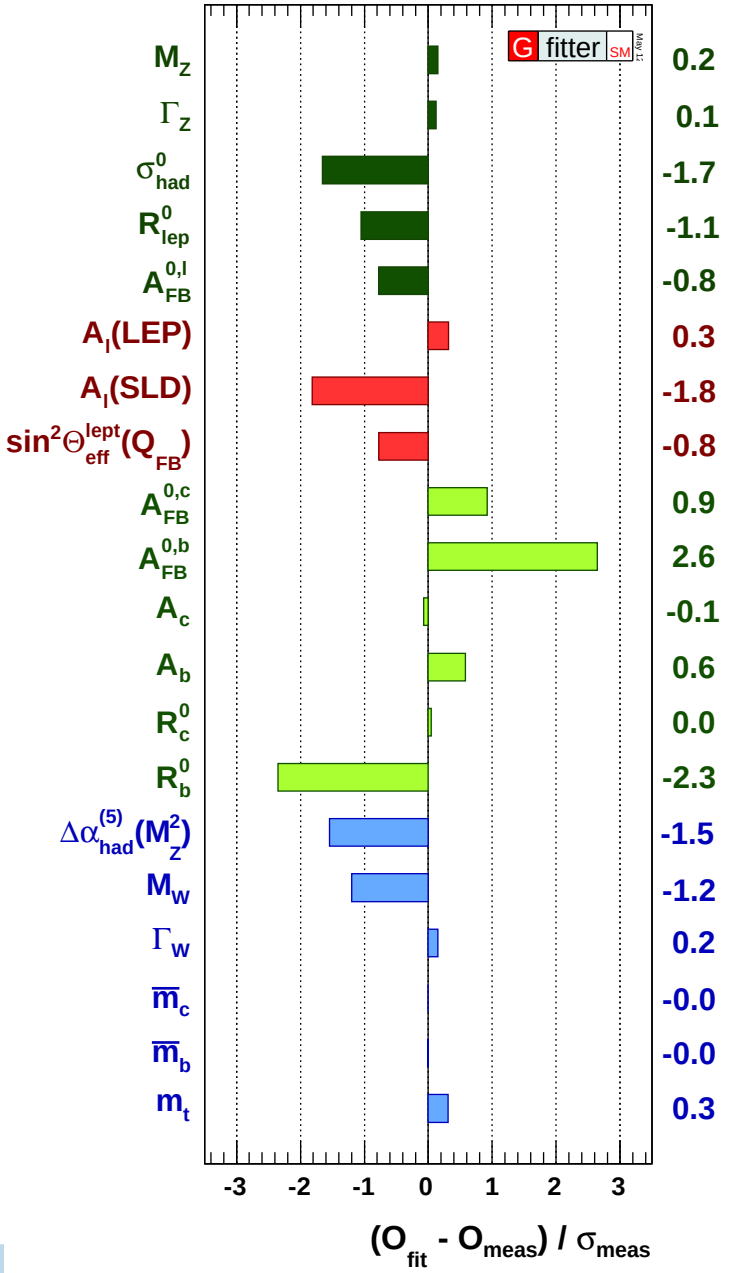


Success of the SM II

Elegant description of nature at per mille precision

- Electroweak precision tests





Success of the SM III

Elegant description of nature at per mille precision

- **CKM-mechanism NP 2008**

How can CP-violation be incorporated in the SM?

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

CKM$^+$: Status of CKM in 2012

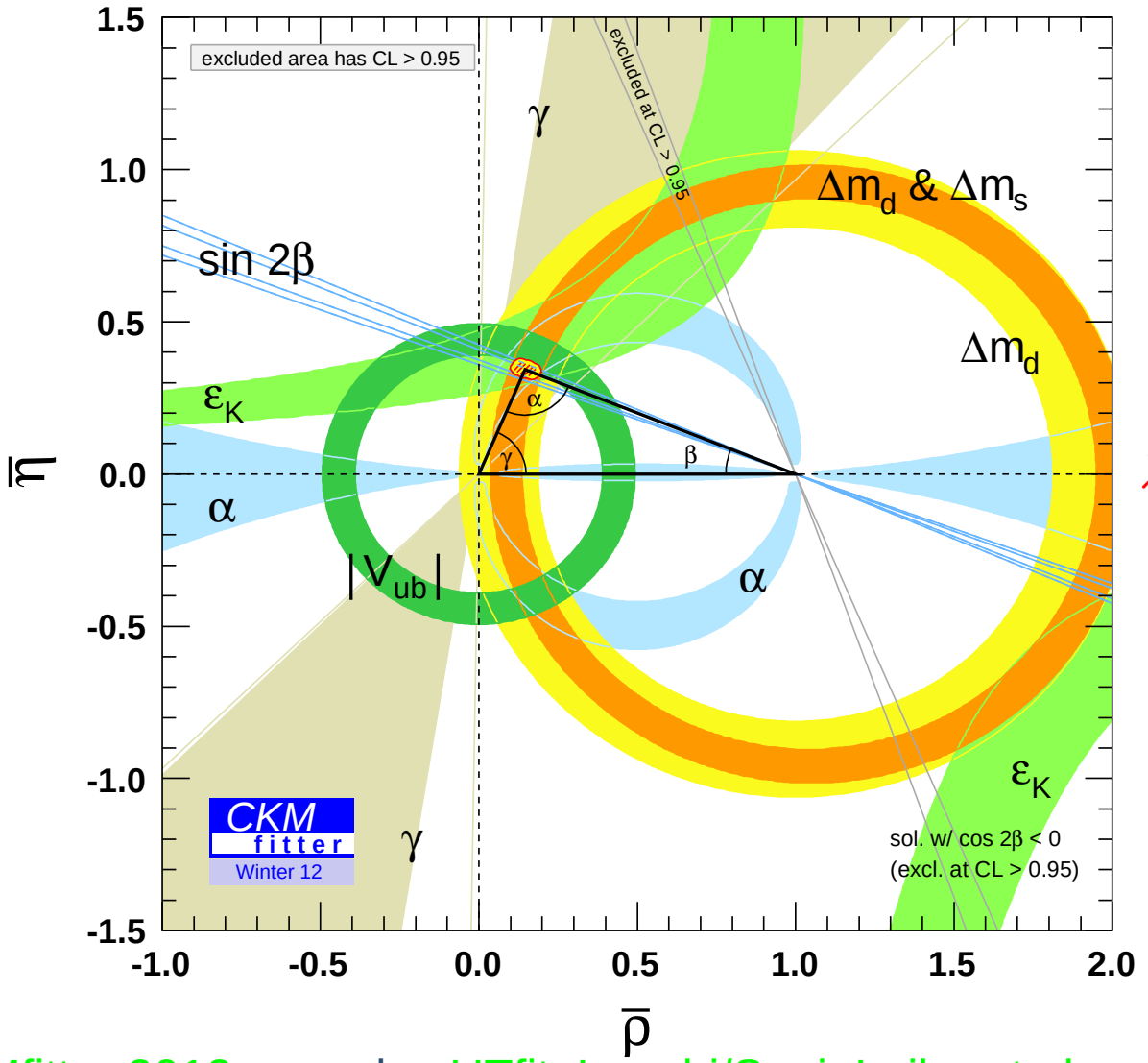
Good overall consistency

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

Fit from CKMfitter 2012

see also UTfit 1010.5089, Lunghi/Soni 1010.6069, Laiho/Lunghi/Van de Water 1102.3917, PDG, HFAG ...

CKM$^+$: The status of CKM in early 2012



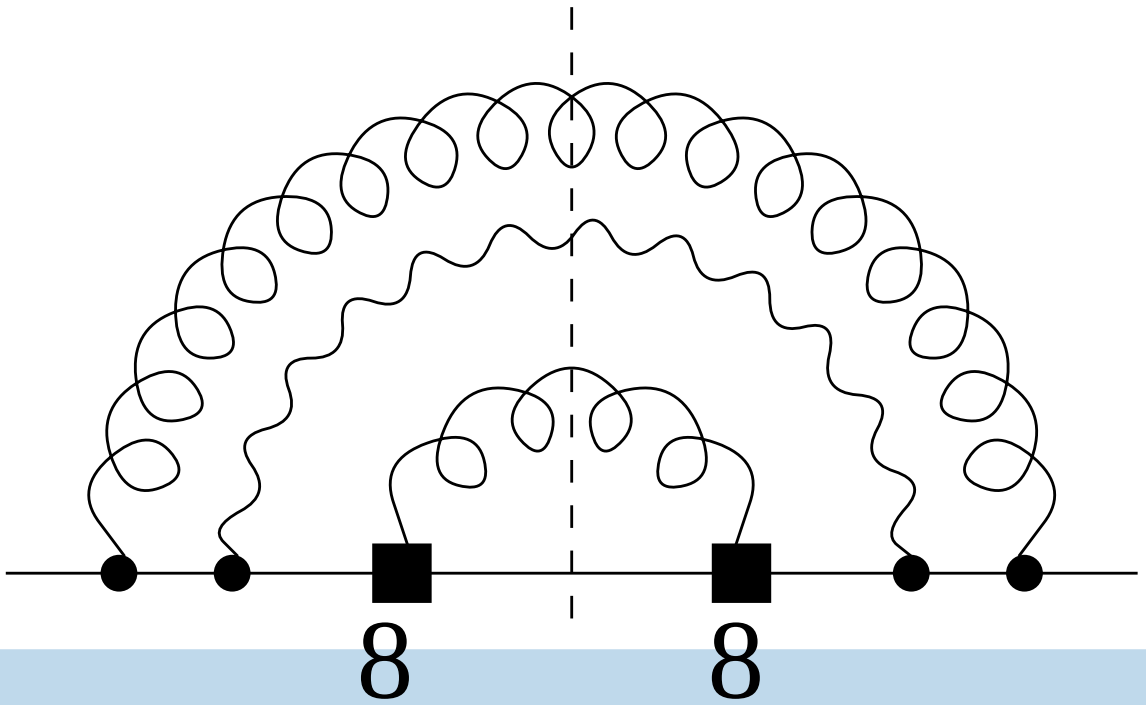
$$A = 0.812^{+0.015}_{-0.022}$$
$$\lambda = 0.22543^{+(59)}_{-(95)}$$
$$\bar{\rho} = 0.145(27)$$
$$\bar{\eta} = 0.343(15)$$

Picture from CKMfitter 2012, see also UTfit, Lunghi/Soni, Laiho et al...

CKM$^+$: $b \to s\gamma$- Another success of CKM

$$Br(b \to s\gamma)^{\rm Exp} = (3.55 \pm 0.26) \cdot 10^{-4}$$
$$Br(b \to s\gamma)^{\rm Theo} = (3.15 \pm 0.23) \cdot 10^{-4}$$

Exp: HFAG, BaBar, BELLE, CLEO
Theory in NNLO Misiak et al. 2007,...
List of References in Misiak, PoS(FPCP 2010)025



CKM^0: The first row: V_{ud}

- Nuclear β-decay
- Neutron β-decay
- Pion β-decay

$$|V_{ud}| = 0.97425 \pm 0.00022$$

PDG 2010, Hardy, Towner 2009

CKM^0: The first row: V_{us}

- K_{l3}-decays
- Hadronic τ decays
- Semi leptonic Hyperon decays

$$|V_{us}| = 0.2254 \pm 0.0013$$

Antonelli et al. 1005.2323; Boyle et al. 1004.0886

CKM^0: The first row: V_{ub}

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	$\lvert V_{ub}\rvert = 0.00356 \pm 0.00020$

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: $0.00356 = (0.2254)^{3.79}$
- 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

CKM^0: The first row: $V_{ub'}$

Test the accuracy of the CKM elements of the first row:

$$\begin{aligned} \delta(V_{ud}) &= 0.00022 \\ \delta(V_{us}) &= 0.00130 \\ \delta(V_{ub}) &= 0.00020 \\ \sqrt{1 - V_{ud}^2 - V_{us}^2} &= 0.00564^{+0.02669}_{-0.00564} \end{aligned}$$

Investigate a hypothetical 4th generation of fermions
Assume V_{CKM4} is unitary

$\Rightarrow V_{ub'}$ **can still be much larger than** V_{ub}: $V_{ub'} < 0.04 \approx \lambda^2$

Bobrowski, A.L., Rohrwild, Riedl, 0902.4883; Buras et al. 2010; Eberhardt, A.L., Rohrwild 1005.3505; Das, London, Sinha, Soffer 1008.4925; Alok, Dighe, London 1011.2634; Soni and Nandi 1011.6091;...

CKM^0: The second row: V_{cd}

- Semi leptonic Charm decays $D \to \pi l \nu$
- Charm Production in Neutrino Interactions

$$|V_{cd}| = 0.230 \pm 0.011$$

PDG 2010

CKM^0: The second row: V_{cs}

- Neutrino Scattering
- On-shell W decays
- Semi leptonic Charm decays

$$|V_{cs}| = 1.023 \pm 0.036$$

PDG 2010

CKM^0: The second row: V_{cb}

- $B \to X_c l \nu$
- $B \to D^{(*)}$ transitions

Inclusive	$\lvert V_{cb}\rvert = (41.85 \pm 0.43 \pm 0.59) \cdot 10^{-3}$
Exclusive	$\lvert V_{cb}\rvert = (38.85 \pm 0.77 \pm 0.84) \cdot 10^{-3}$

HFAG 2010; Gambino/Uraltsev (2004); Benson/Bigi/Uraltsev (2005); Benson/Bigi/Mannel/Uraltsev (2003);...

- Inclusive is again larger
- Try to make some combinations

$$|V_{cb}| = \begin{cases} (40.6 \pm 1.3) \cdot 10^{-3} & \text{PDG 2010} \\ (40.89 \pm 0.38 \pm 0.59) \cdot 10^{-3} & 1008.1593 \end{cases}$$

CKM^0: The second row: $V_{cb'}$

Test the accuracy of the CKM elements of the second row:

$$\begin{aligned} \delta(V_{cd}) &= 0.011 \\ \delta(V_{cs}) &= 0.036 \\ \delta(V_{cb}) &= 0.013 \end{aligned}$$

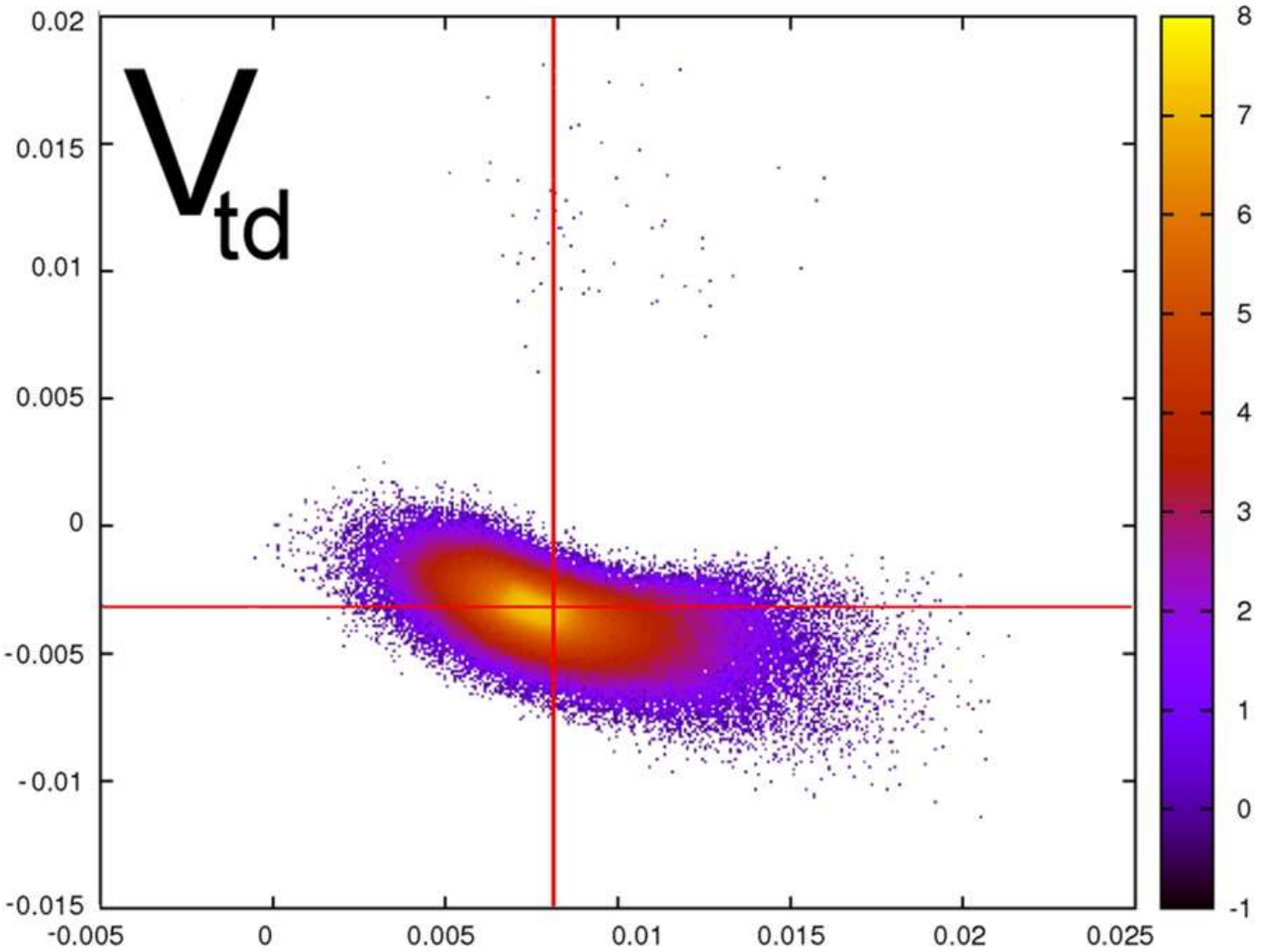
Investigate a hypothetical 4th generation of fermions
Assume V_{CKM4} is unitary

$\Rightarrow V_{cb'}$ **can still be much larger than** V_{cb}: $V_{cb'} < 0.15 \approx \lambda$

Bobrowski, A.L., Rohrwild, Riedl, 0902.4883; Buras et al. 2010; Eberhardt, A.L., Rohrwild 1005.3505; Das, London, Sinha, Soffer 1008.4925; Alok, Dighe, London 1011.2634; Soni and Nandi 1011.6091;

CKM^0: The third row: V_{td}

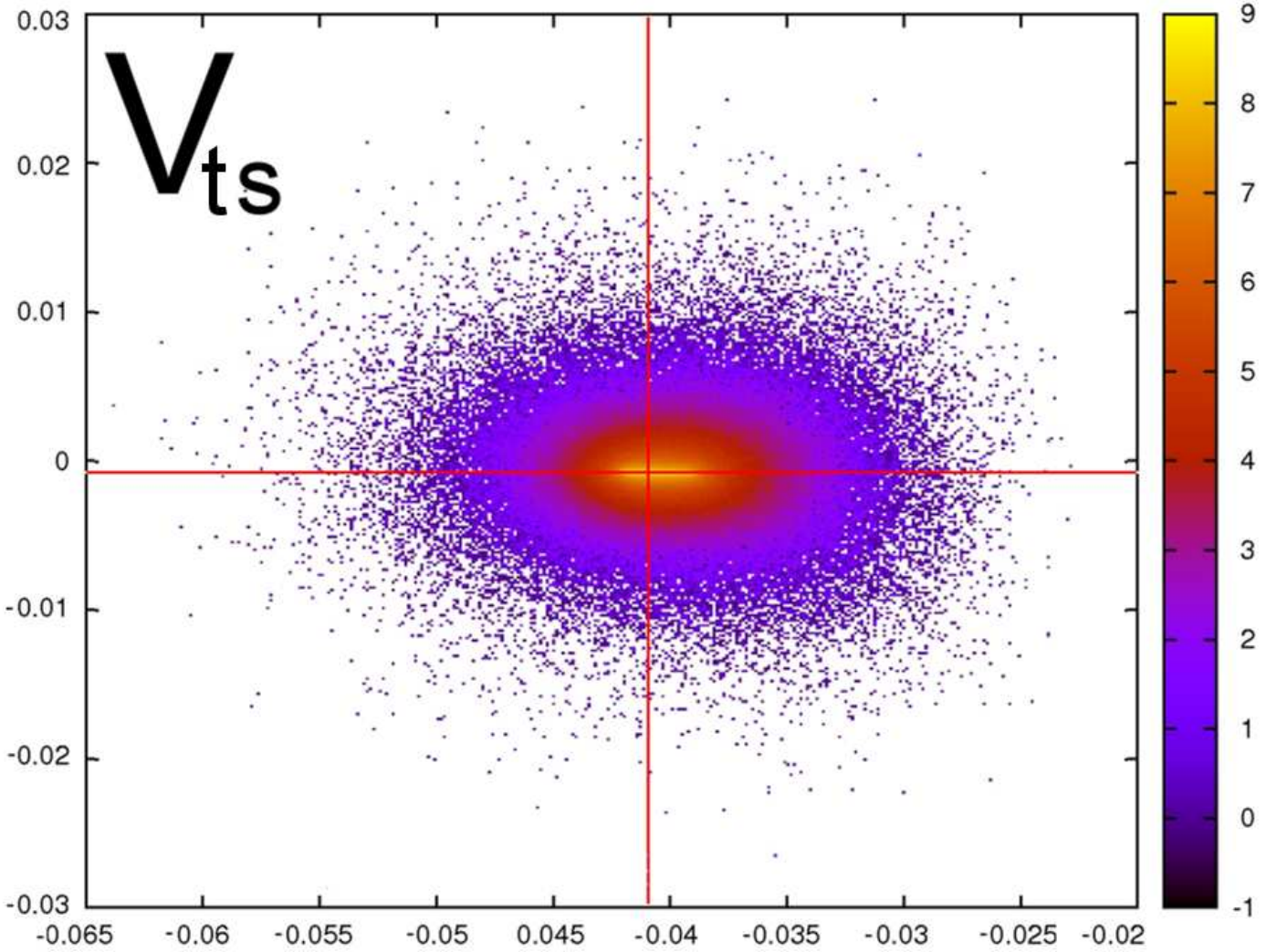
Im V_{td} vs. Re V_{td}



Eberhardt, A.L., Rohrwild 1005.3505

CKM^0: The third row: V_{ts}

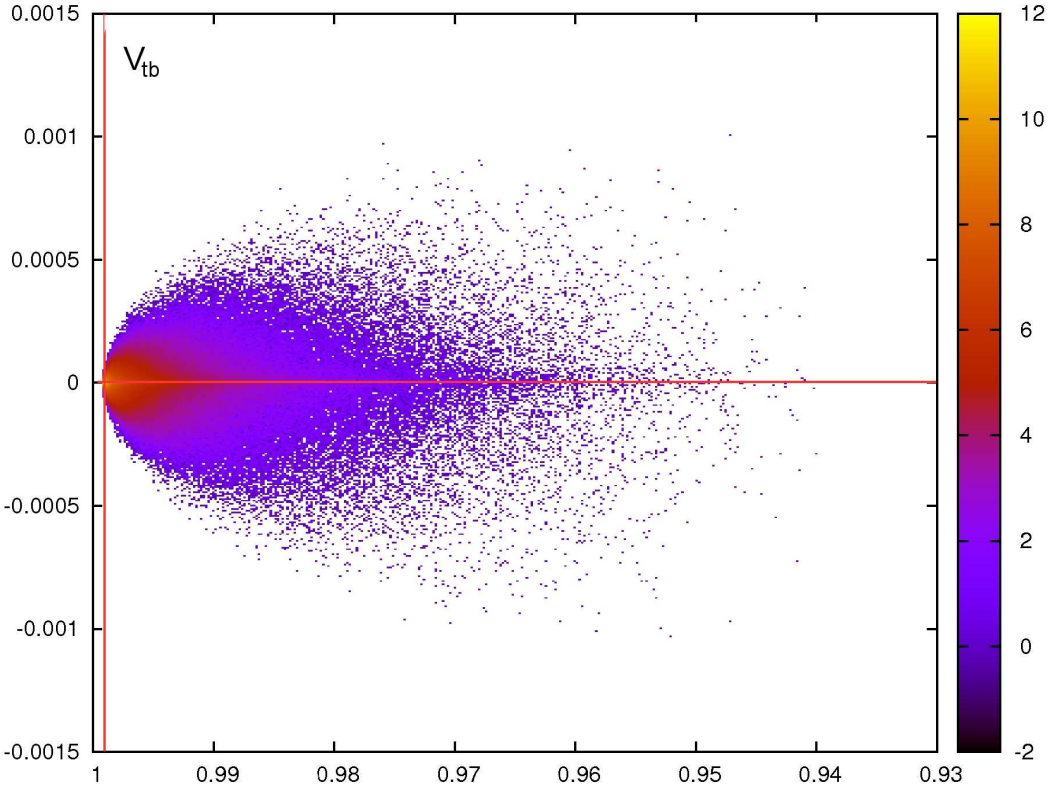
V_{ts} vs. Re V_{ts}



Eberhardt, A.L., Rohrwild 1005.3505

CKM^0: The third row: V_{tb}

Im V_{tb} vs. Re V_{tb}



Eberhardt, A.L., Rohrwild 1005.3505

Single Top production Wagner 1101.4235; CDF 0903.0885,1004.1181; D0 0903.0850

$$V_{tb} = 0.88 \pm 0.07$$

CKM^0: The CKM values should be known better!

- Overall picture looks very good: CKM$^+$
- But looking in more detail: CKM^0
  - more precise value of V_{us} desireable
  - V_{ub} problem
  - more precise values of V_{cx} needed
  - (almost) no direct information on V_{tx}

There is still a lot of room for deviations $\Rightarrow$ Look for it — LHCb, SuperB-factories

- It becomes worse (or more interesting?): CKM$^-$

There are several hints for deviations from the CKM picture!

CKM⁻: Flavor Physics in the news

- 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
- ...

The dimuon asymmetry

- 1005.2757 Dzero (submitted sunday, 16.5.2010) 195 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.

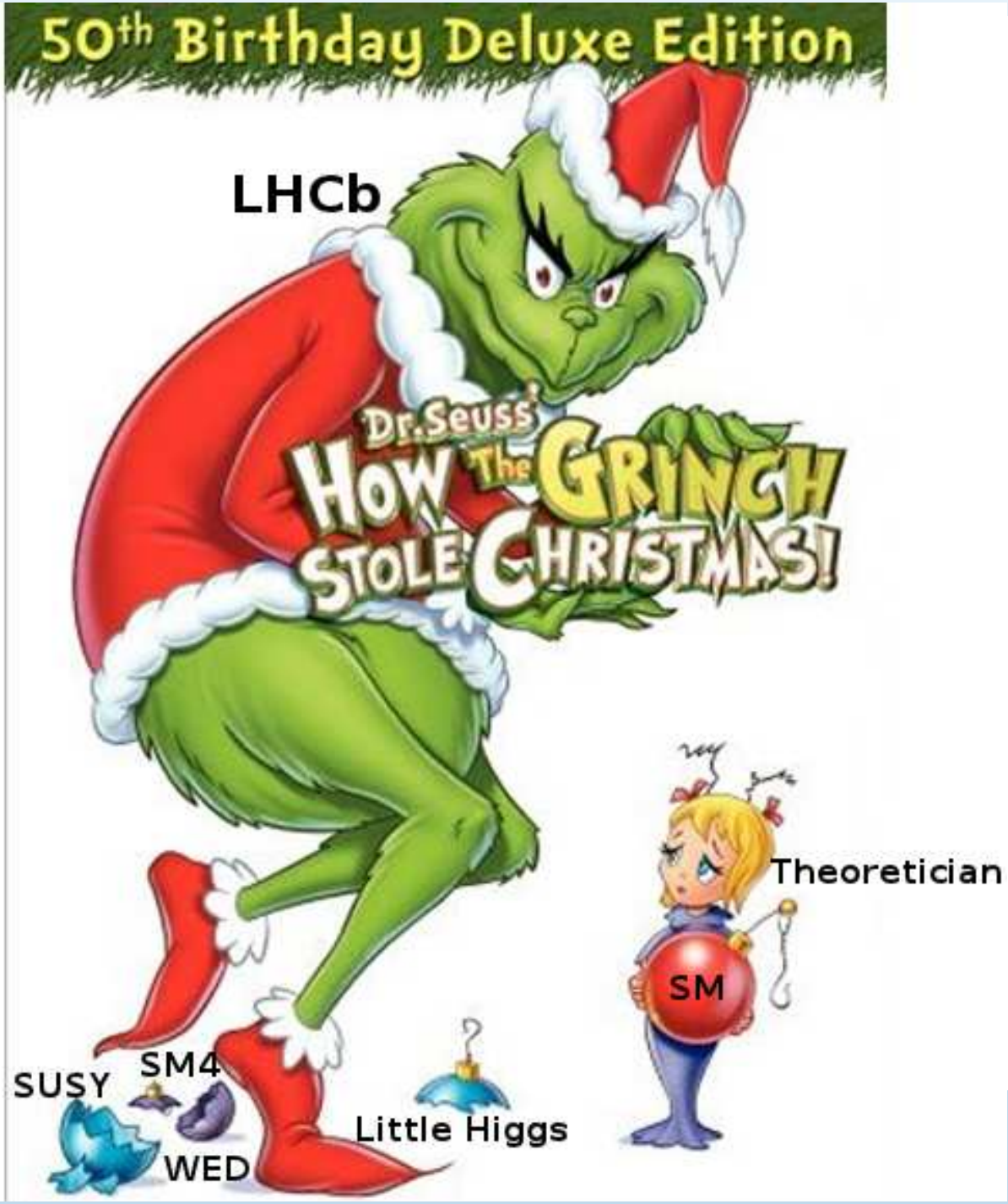
DOI: 10.1103/PhysRevD.82.032001 PACS numbers: 13.25.Hw, 11.30.Er, 14.40.Nd

[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" ($111 \cdot 10^6$ google entries)

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

TeVatron gave us many presents, and then ...

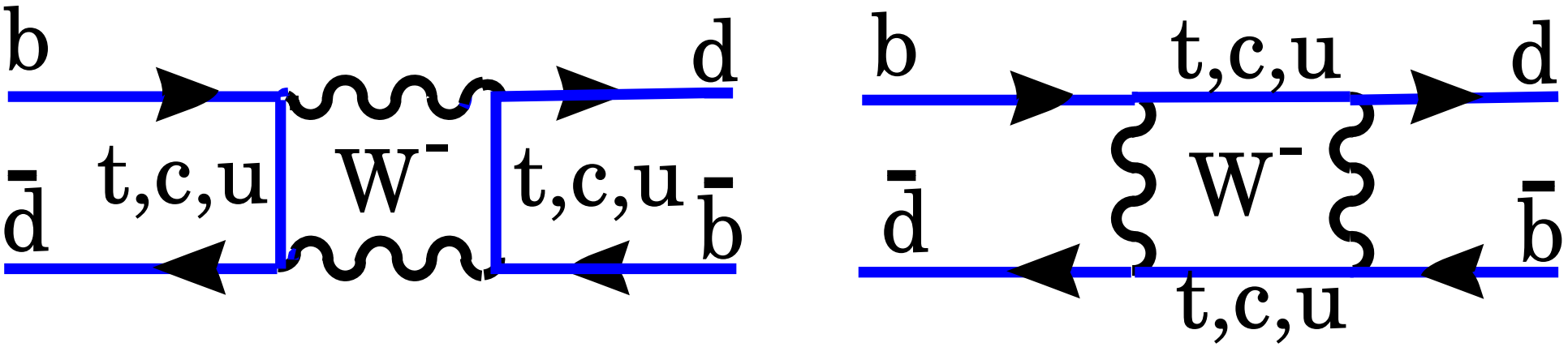


Mixing I

Time evolution of a decaying particle: $B(t) = \exp\left[-im_B t - \Gamma_B/2t\right]$ can be written as

$$i\frac{d}{dt}\begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix} = \left(\hat{M} - \frac{i}{2}\hat{\Gamma}\right)\begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix}$$

BUT: In the neutral B-system transitions like $B_{d,s} \to \bar{B}_{d,s}$ are possible due to weak interaction: **Box diagrams**



Mixing II

Mixing is a macroscopic quantum effect!

It was observed in

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

Strongly suppressed in the SM (due to virtual top-quarks)
New physics effects might be of comparable size

?Is QCD under control?

Mixing III

Time evolution of a decaying particle: $B(t) = \exp\left[-im_B t - \Gamma_B/2t\right]$ can be written as

$$i\frac{d}{dt}\begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix} = \left(\hat{M} - \frac{i}{2}\hat{\Gamma}\right)\begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix}$$

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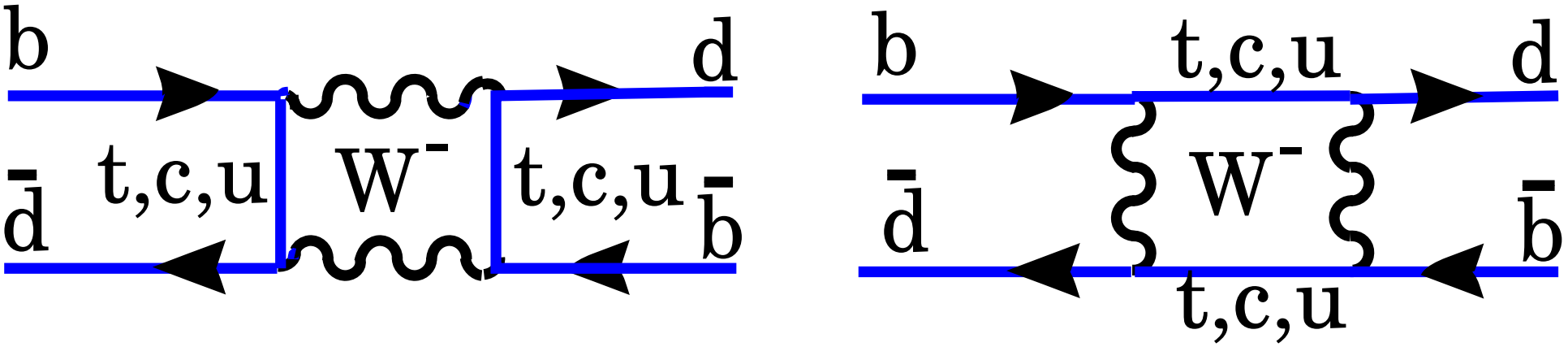

$\Rightarrow$ **off-diagonal elements** in $\hat{M}$, $\hat{\Gamma}$: M_{12}, Γ_{12} (complex)

Diagonalization of $\hat{M}$, $\hat{\Gamma}$ gives the physical eigenstates B_H and B_L with the masses M_H, M_L and the decay rates Γ_H, Γ_L

CP-odd: $B_H := p\,B + q\,\bar{B}$, CP-even: $B_L := p\,B - q\,\bar{B}$ with $|p|^2 + |q|^2 = 1$

Mixing IV

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

- **Mass difference:** $\Delta M := M_H - M_L = 2|M_{12}| \left(1 - \frac{1}{8}\frac{|\Gamma_{12}|^2}{|M_{12}|^2}\sin^2\phi + ...\right)$
  $|M_{12}|$: heavy internal particles: t, SUSY, ...

- **Decay rate difference:** $\Delta\Gamma := \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos\phi \left(1 + \frac{1}{8}\frac{|\Gamma_{12}|^2}{|M_{12}|^2}\sin^2\phi + ...\right)$
  $|\Gamma_{12}|$: light internal particles: u, c, ... (almost) no NP!!!

- **Flavor specific/semileptonic CP asymmetries:**
  $\bar{B}_q \to f$ and $B_q \to \bar{f}$ forbidden
  No direct CP violation: $|\langle f|B_q\rangle| = |\langle \bar{f}|\bar{B}_q\rangle|$
  e.g. $B_s \to D_s^- \pi^+$ or $B_q \to X l \nu$ (*semileptonic*)

$$a_{sl} \equiv a_{fs} = \frac{\Gamma(\overline{B}_q(t) \to f) - \Gamma(B_q(t) \to \overline{f})}{\Gamma(\overline{B}_q(t) \to f) + \Gamma(B_q(t) \to \overline{f})} = -2\left(\left|\frac{q}{p}\right| - 1\right) = \mathrm{Im}\frac{\Gamma_{12}}{M_{12}} = \frac{\Delta\Gamma}{\Delta M}\tan\phi$$

The Mass Difference ΔM

Calculating the box diagram with an internal top-quark yields

$$M_{12,q} = \frac{G_F^2}{12\pi^2}(V_{tq}^* V_{tb})^2 M_W^2 S_o(x_t) B_{B_q} f_{B_q}^2 M_{B_q} \hat{\eta}_B$$

(Inami, Lim '81)

- Hadronic matrix element: $\frac{8}{3} B_{B_q} f_{B_q}^2 M_{B_q} = \langle \bar{B}_q | (\bar{b}q)_{V-A} (\bar{b}q)_{V-A} | B_q \rangle$
- Perturbative QCD corrections $\hat{\eta}_B$ (Buras, Jamin, Weisz, '90)

Theory 1102.4274 vs. Experiment : HFAG 11

$\Delta M_d = 0.543 \pm 0.091\ ps^{-1}$	$\Delta M_d = 0.507 \pm 0.004\ ps^{-1}$
	ALEPH, CDF, D0, DELPHI, L3,
	OPAL, BABAR, BELLE, ARGUS, CLEO
$\Delta M_s = 17.30 \pm 2.6\ ps^{-1}$	$\Delta M_s = 17.69 \pm 0.08\ ps^{-1}$
	CDF, D0, LHCb

Important bounds on the unitarity triangle and new physics

Determination of Γ_{12}

Sensitive to real intermediate states $\Rightarrow$ much more complicated than M_{12}

1. OPE I: Integrate out W: like $M_{12} \propto f_B^2 B$
2. OPE II: Heavy quark expansion $\Rightarrow \Gamma_i^{(j)} \propto f_B^2 \sum C_k B_K$

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

1996: Beneke, Buchalla, Dunietz

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

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

2006: A.L., Nierste

2007: Badin, Gabbiani, Petrov

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

HQE under attack!

OPE II might be questionable - relies on quark hadron duality

- 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
- 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
$\Rightarrow \Gamma_{12}$ seems to be ok!

$\Rightarrow$ test reliability of OPE II via lifetimes (no NP effects expected) "directions", to test convergence
$\Rightarrow \tau(B^+)/\tau(B_d)$ Experiment and theory agree within hadronic uncertainties

HQE under attack!

OPE II might be questionable - relies on quark hadron duality

- 2012: $n_c^{2011\mathrm{PDG}} = 1.20 \pm 0.06$ vs. $n_c^{\mathrm{SM}} = 1.20 \pm 0.04$
  Eberhardt, Krinner, A.L., Rauh in prep.
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- HFAG '03 $\tau_{\Lambda_b} = 1.229 \pm 0.080$ ps^{-1} $\longrightarrow$ HFAG '11 $\tau_{\Lambda_b} = 1.425 \pm 0.032$ ps^{-1}
  Shift by 2.5σ $\Rightarrow$Eagerly waiting for new LHCb results!!!
- before 2003: $\tau_{B_s}/\tau_{B_d} \approx 0.94 \neq 1$
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- **Moriond 2012 LHCb:** $\tau_{B_s}/\tau_{B_d} = 1.001 \pm 0.014$ LHCb-CONF-2012-002
- 2010/2011: Di-muon asymmetry too large

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$\Rightarrow$ calculate corrections in all possible "directions", to test convergence
$\Rightarrow \Gamma_{12}$ seems to be ok!

$\Rightarrow$ test reliability of OPE II via lifetimes (no NP effects expected) "directions", to test convergence
$\Rightarrow \tau(B^+)/\tau(B_d)$ Experiment and theory agree within hadronic uncertainties

The B_s lifetime

Moriond 2012 LHCb vs SM A.L., Nierste 2011

$$\frac{\tau_{B_s}}{\tau_{B_d}}^{\rm Exp} = 1.001 \pm 0.014 \qquad \frac{\tau_{B_s}}{\tau_{B_d}}^{\rm SM} = 0.996...1.000$$

- 0.940 ± 0.014 would have been a desaster for SM = may be NP :-)
- Update of effective lifetimes
  Fleischer et al used 1011.1096, 1109.1112, 1109.5115: τ_{B_s} = 1.477 ps

	Exp.	SM-old	SM-new
$\tau^{\rm Eff}(K^+K^-)$	1.468 ± 0.046	1.390 ± 0.032	1.43 ± 0.03
$\tau^{\rm Eff}(\psi f_0)$	1.70 ± 0.12	1.582 ± 0.036	1.63 ± 0.03
$\tau^{\rm FS}$	1.463 ± 0.032	$---$	1.54 ± 0.03

HQE under attack!

OPE II might be questionable - relies on quark hadron duality

- 2012: $n_c^{2011\mathrm{PDG}} = 1.20 \pm 0.06$ vs. $n_c^{\mathrm{SM}} = 1.20 \pm 0.04$
  Eberhardt, Krinner, A.L., Rauh in prep.
- HFAG '03 $\tau_{\Lambda_b} = 1.229 \pm 0.080$ ps^{-1} $\longrightarrow$ HFAG '11 $\tau_{\Lambda_b} = 1.425 \pm 0.032$ ps^{-1}
  Shift by 2.5σ $\Rightarrow$Eagerly waiting for new LHCb results!!!
- **Moriond 2012 LHCb:** $\tau_{B_s}/\tau_{B_d} = 1.001 \pm 0.014$ LHCb-CONF-2012-002
- 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
$\Rightarrow \Gamma_{12}$ seems to be ok!

$\Rightarrow$ test reliability of OPE II via lifetimes (no NP effects expected) "directions", to test convergence
$\Rightarrow \tau(B^+)/\tau(B_d)$ Experiment and theory agree within hadronic uncertainties

$\Delta\Gamma_s$ in NLO-QCD I

A brief history of theory predictions

'81... Hagelin; Buras et al.;...	$\Delta\Gamma \propto \mathcal{O}\left(0.15\ \text{ps}^{-1}\right)$
'93 Aleksan et al.; ...	$\Delta\Gamma \propto \mathcal{O}\left(0.10\ \text{ps}^{-1}\right)$
'96 Beneke, Buchalla, Dunietz	$\Delta\Gamma_s = \left(0.11^{+0.07}_{-0.06}\right)\text{ps}^{-1}$
'03 Ciuchini, et al	$\Delta\Gamma_s = (0.050 \pm 0.016)\,\text{ps}^{-1}$
'06 A.L., Nierste	$\Delta\Gamma_s = (0.096 \pm 0.036)\,\text{ps}^{-1}$
'11 A.L., Nierste	$\Delta\Gamma_s = (0.087 \pm 0.021)\,\text{ps}^{-1}$
'12 Ciuchini et al	$\Delta\Gamma_s = (0.098 \pm 0.010)\,\text{ps}^{-1}$

Crucial dependence on non-perturbative parameters!

2011 $f_{B_s} = 231 \pm 15$ MeV used.

Newer Results:

- 1110.4510 - HPQCD: $f_{B_s} = 225 \pm 4$ MeV $\Rightarrow \Delta\Gamma_s = (0.083 \pm 0.017)\,\text{ps}^{-1}$
- 1112.3051 - Fermilab: $f_{B_s} = 242 \pm 9.5$ MeV $\Rightarrow \Delta\Gamma_s = (0.095 \pm 0.021)\,\text{ps}^{-1}$
- 1201.3956 - chiral QM: $f_{B_s} = 262 \pm ?$ MeV $\Rightarrow \Delta\Gamma_s = (0.112 \pm ?)\,\text{ps}^{-1}$

$\Delta\Gamma_s$ in NLO-QCD II

Improvement in theoretical accuracy

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

Finally $\Delta\Gamma_s$ is measured! (naive: 6.1σ)

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

LHCb from $B_s \to J/\psi\phi$ Dunietz, Fleischer, Nierste

LP 2011 $\Delta\Gamma_s = (0.123 \pm 0.031)\,{\rm ps}^{-1} \Rightarrow \dfrac{\Delta\Gamma_s^{\rm Exp}}{\Delta\Gamma_s^{\rm SM}} = 1.41 \pm 0.50$

Moriond 2012 $\Delta\Gamma_s = (0.116 \pm 0.019)\,{\rm ps}^{-1} \Rightarrow \dfrac{\Delta\Gamma_s^{\rm Exp}}{\Delta\Gamma_s^{\rm SM}} = 1.33 \pm 0.39$

- D0 8fb^{-1} 1109.3166: $\Delta\Gamma_s = (0.163 \pm 0.065)\,{\rm ps}^{-1}$
- CDF 9.6fb^{-1} Public Note 10778: $\Delta\Gamma_s = (0.068 \pm 0.027)\,{\rm ps}^{-1}$

$$\Delta\Gamma_s^{\rm Exp} = (0.100 \pm 0.013)\,{\rm ps}^{-1}$$

HFAG 2012

Finally $\Delta\Gamma_s$ is measured! (naive: 6.1σ)

Get rid off the dependence on f_{B_s} (No NP in ΔM)

$$\begin{aligned}\frac{\Delta\Gamma_s}{\Delta M_s} &= 10^{-4}\cdot\left[46.2+10.6\frac{\tilde{B}'_S}{B}-\left(13.2\frac{B_{\tilde{R}_2}}{B}-2.5\frac{B_{R_0}}{B}+1.2\frac{B_R}{B}\right)\right]\\ &= 0.0050\pm 0.0010\end{aligned}$$

HQE vs. Experiment

$$\left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^{\rm Exp}\Big/\left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^{\rm SM} = 1.12\pm 0.27$$

HQE works also for Γ_{12}!

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

Still more accurate data needed! **TeVatron, LHCb, Super-B(elle)**

$\Delta\Gamma_s^{\rm CP}/\Gamma_s = 2Br(B_s \to D_s^{(*)+} + D_s^{(*)-})$?

- 1993 Aleksan; Le Yaouanc, Olivre, Pene, Raynal:
  The above equation holds in the limit: $m_c \to \infty; m_b - 2m_c \to 0; N_c \to \infty$
  Corresponds to negligible 3-body final state contributions to Γ_{12}^s

$$\frac{\Delta\Gamma_s}{\Gamma_s} \propto \mathcal{O}(0.15)$$

- 1107.4325 Chua, Hou, Shen Reanalysis of the exclusive approach
  - 2-body final states contribute 0.100 ± 0.030 to $\Delta\Gamma/\Gamma$
    Aleksan et al were lucky...
  - 3-body final states contribute about 0.06...0.08
    This is comparable to 2-body final states! $\Rightarrow$ bad approximation $\Rightarrow$ test exp.

We strongly discourage from the inclusion of $Br(Bs \to D^{(*)+} + D^{(*)-})$ in averages with $\Delta\Gamma_s$ determined from clean methods.

A.L., Nierste; hep-ph/0612167

Semi leptonic CP-asymmetries a_{fs} and $\Delta\Gamma_d$

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

$$a_{fs}^s = (1.9 \pm 0.3) \cdot 10^{-5} \qquad \phi_s = 0.22^\circ \pm 0.06^\circ$$
$$a_{fs}^d = -(4.1 \pm 0.6) \cdot 10^{-4} \qquad \phi_d = -4.3^\circ \pm 1.4^\circ$$
$$A_{sl}^b = 0.406 a_{sl}^s + 0.594 a_{sl}^d = (-2.3 \pm 0.4) \cdot 10^{-4}$$

Experimental bounds

$$a_{fs}^s = (-1050 \pm 640) \cdot 10^{-5} \text{ (HFAG 12)}$$
$$\phi_s = -51.6^\circ \pm 12^\circ \quad \text{(A.L., Nierste, CKMfitter, 1008.1593)}$$
$$= -0.1^\circ \pm 5.0^\circ \quad \text{LHCb Moriond 2012}$$
$$a_{fs}^d = -(33 \pm 33) \cdot 10^{-4} \quad \text{(HFAG 12)}$$
$$\frac{\Delta\Gamma_d}{\Gamma_d} = (-17 \pm 21) \cdot 10^{-3} \quad \text{(Belle EPS 2011)}$$
$$A_{sl}^b = -(7.87 \pm 1.72 \pm 0.93) \cdot 10^{-3} \text{(D0,1106.6308)}$$

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

New Physics in B-Mixing I

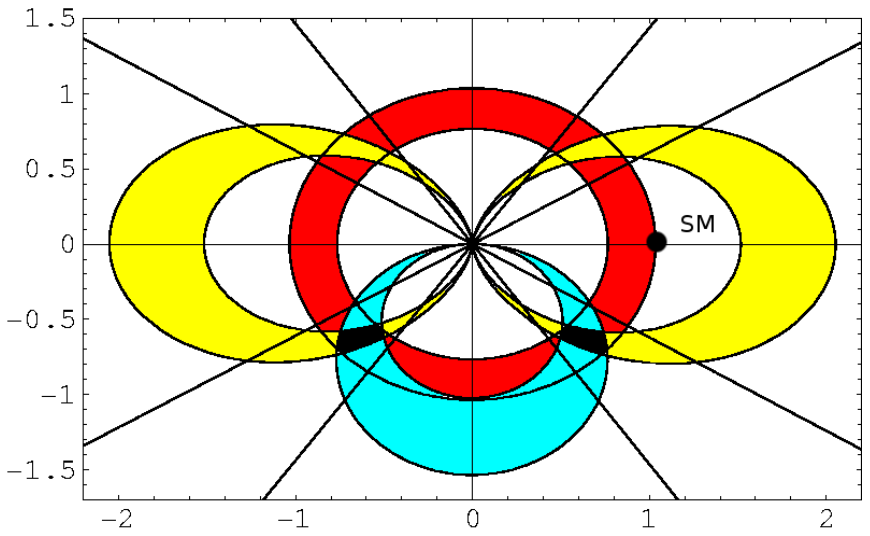
$$\Gamma_{12,s} = \Gamma_{12,s}^{\rm SM}\,, \qquad M_{12,s} = M_{12,s}^{\rm SM}\cdot\Delta_s\,; \quad \Delta_s = |\Delta_s| e^{i\phi_s^\Delta}$$

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

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

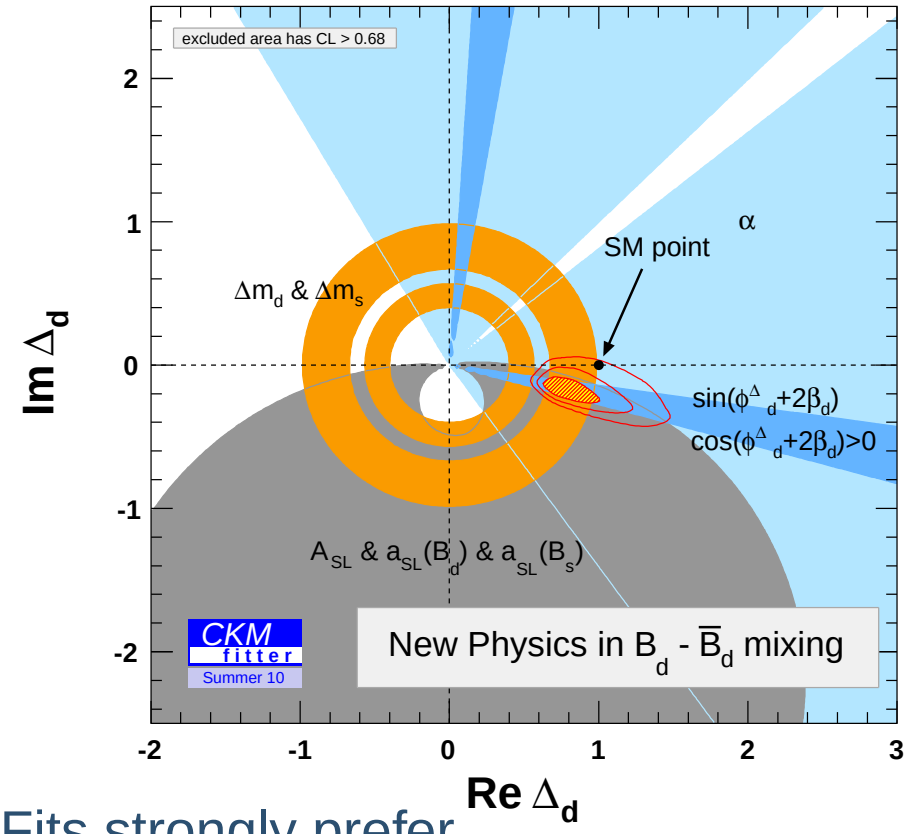
$$\sin(\phi_s^{\rm SM}) \approx 1/240$$

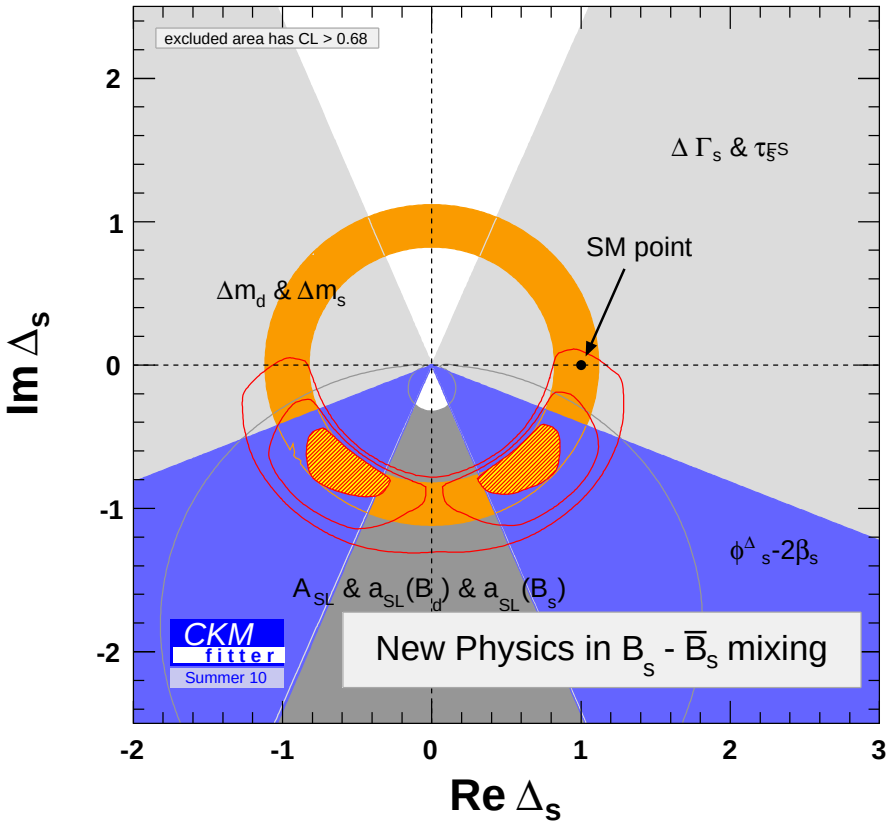
For $|\Delta_s| = 0.9$ and $\phi_s^\Delta = -\pi/4$ one gets the following bounds in the **complex Δ-plane**:



New Physics in B-Mixing II

Combine all data before summer 2010 and neglect penguins
fit of Δ_d and Δ_s 1008.1593



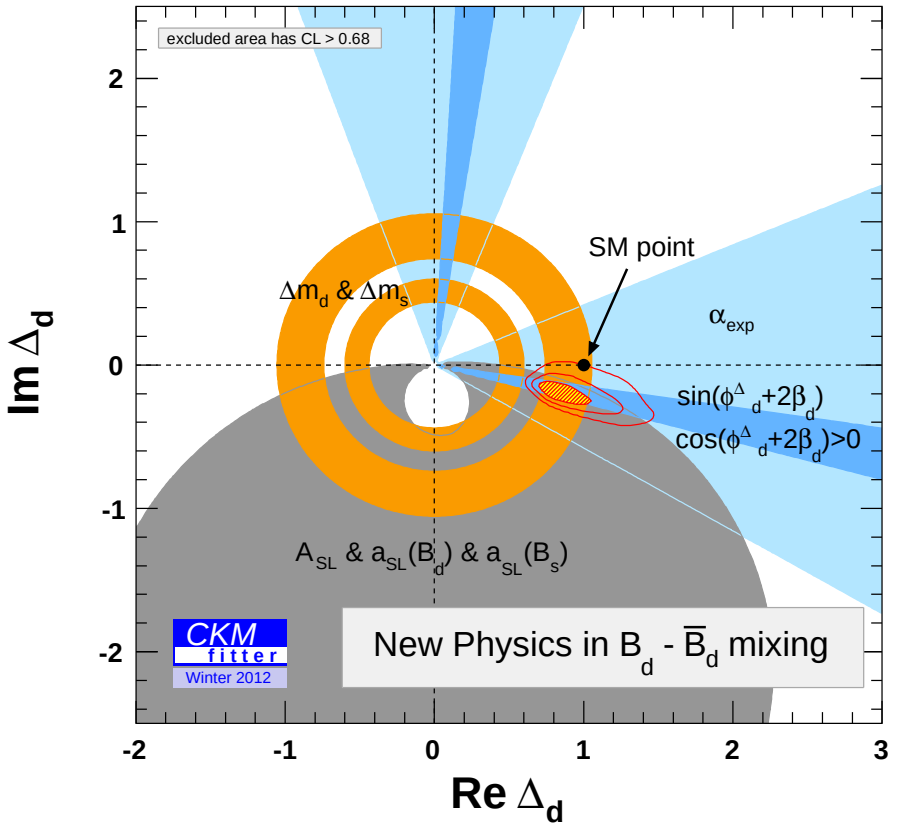


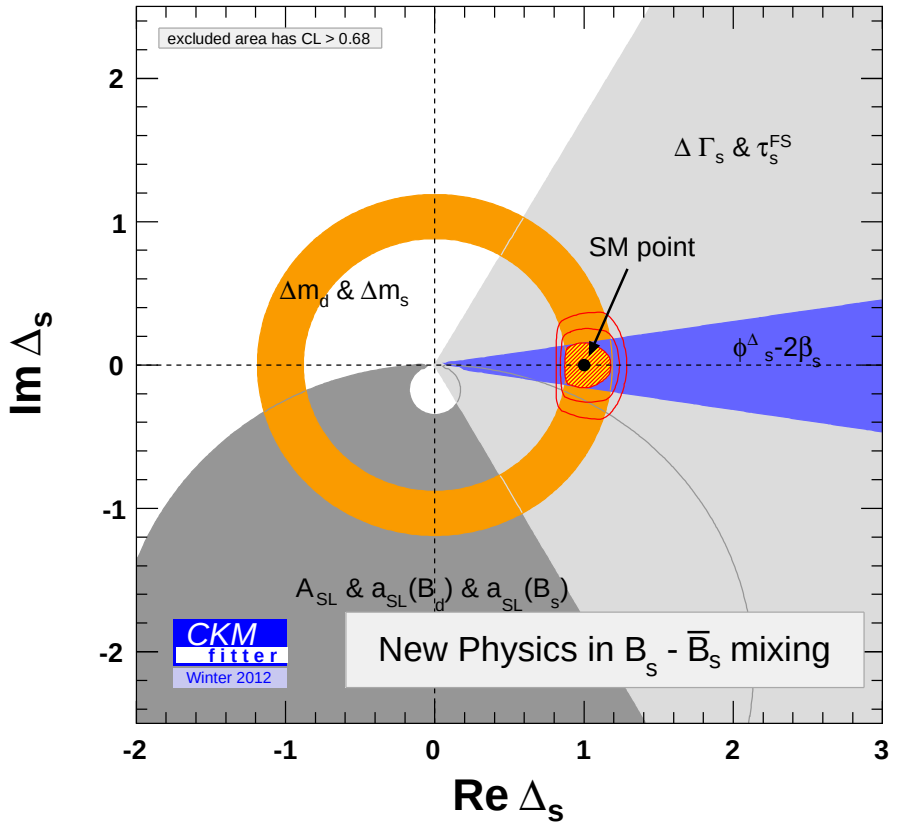
Fits strongly prefer

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

New Physics in B-Mixing II

Combine all data till now and neglect penguins
fit of Δ_d and Δ_s 1203.0238v2





- Fits not so good anymore (LHCb vs. Dzero) - still sizeable room
- $B \to \tau\nu$ vs. $\sin 2\beta$ solved with ϕ_d^{Δ} — No tension for ϵ_K

The dimuon asymmetry

The central value of the diμasymmetry is larger than *theoretically* possible!

$$\begin{aligned} A_{sl} &\approx (0.594 \pm 0.022)(5.4 \pm 1.0) \cdot 10^{-3} \frac{\sin(\phi_d^{SM} + \phi_d^{\Delta})}{|\Delta_d|} \\ &\quad + (0.406 \pm 0.022)(5.0 \pm 1.1) \cdot 10^{-3} \frac{\sin(\phi_s^{SM} + \phi_s^{\Delta})}{|\Delta_s|} \\ &\leq (-1.7[1\sigma]; -2.8[3\sigma]) \cdot 10^{-3} \\ A_{sl}^{D0} &= (-7.8 \pm 2.0) \cdot 10^{-3} \end{aligned}$$

A.L. 1205.1444

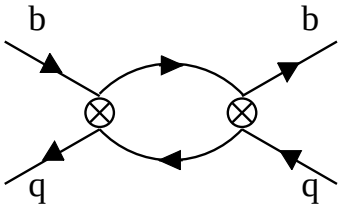
Possible solutions:

- HQE violated by $\mathcal{O}(200\% - 3300\%)$ now excluded!
- Huge new physics in Γ_{12}? - No! Bobeth, Haisch 1109.1826
- Contradiction to $B_s \to J/\psi\phi$ from LHCb? - Be aware of Penguins!
- Stat. fluctuation (2.5 σ) of the D0 result? (Actual value is below -2.8 per mille?) Independent measurements of semi leptonic asymmetries needed!

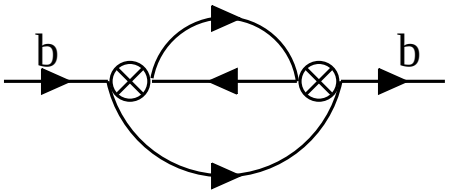
?New physics in Γ_{12}?

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

  The average number of charm quarks per b-decay reads

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

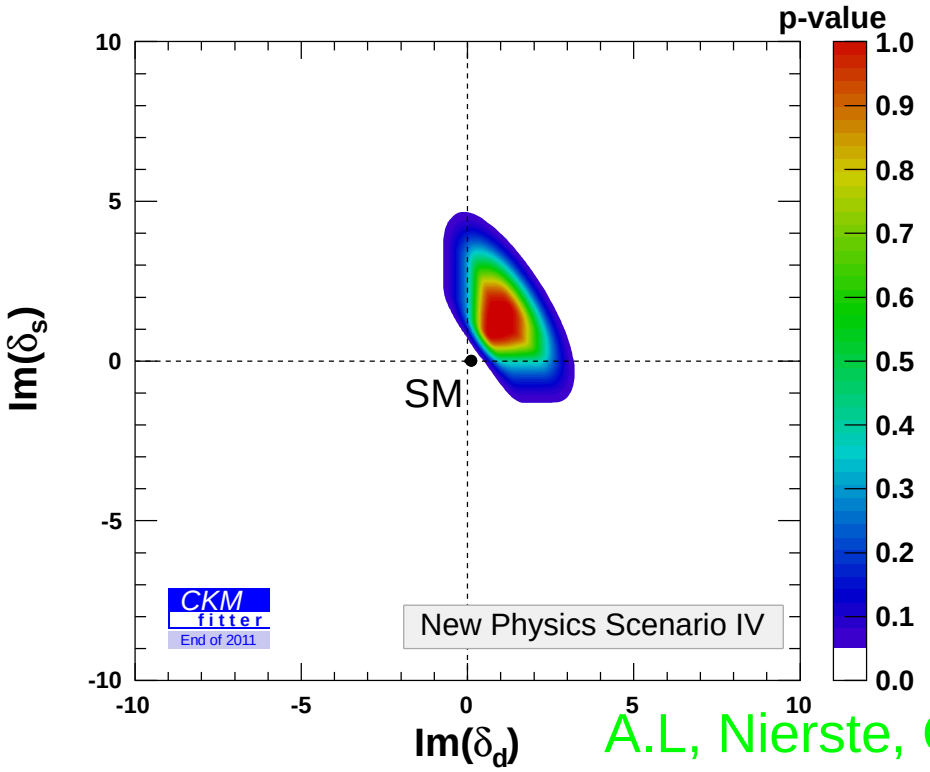
  Buchalla, Dunietz, Yamamoto '95

  - $n_c^{\text{Exp.}} < n_c^{\text{Theory}}$ = 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}!!!

?New physics in Γ_{12}?

Step I: Forget about all the bounds and fit $\Delta\Gamma$, a_{sl} and ΔM:



A.L, Nierste, CKMfitter 1203.0238

Step II: Take your favourite model which gives new contributions to Γ_{12}

- Determine contributions to δ_d, δ_s
- Determine contributions to τ_{B_s}, n_c, ...
- *Exclude the model :-)*

How large are Penguins?

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

$$S_{\psi\phi}^{\rm SM} = 0.0036 \pm 0.002 \to \sin\left(2\beta_s - \phi_s^{\Delta} - \delta_s^{\rm Peng,SM} - \delta_s^{\rm Peng,NP}\right) = 0.002 \pm 0.087$$

LHCb Moriond 2012

Is this a contraction to the dimuon asymmetry?

Depends on the possible size of penguin contributions

- SM penguin are expected to be very small
  but see also Faller, Fleischer; Mannel 2008
- NP penguins might be larger

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

Conclusions

- Experimental proof of our theoretical tools

$$\Delta\Gamma_s^{\rm SM} = \Delta\Gamma_s^{\rm Exp}$$

  - Heavy Quark Expansion works well for b
  - Violations of Quark Hadron duality cannot be huge

- No huge NP effects in B-mixing
  - Hints for NP effects in the B_d-system at the 2-3 σ-level
  - Still some room for NP effects in B_s mixing
  - Tomorrow AJB: Consequences of theses results and e.g. $B_s \to \mu\mu$ for concrete models of NP

- There are many new, interesting results for the charm-system
  Now we learnt the HQE works very well for the b-system.
  Does this tell us something about the c-system?

Moriond 2012: Conclusion from B-Mixing

It is actually not bad, what the Grinch left for us

Expansion in $1/m_b$ works so well,

What does this tell about charm? $1/m_c \approx 3 \cdot 1/m_b$

Wish-list for Experiments

a) **Congratulations to LHCb for the first measurement of $\Delta\Gamma_s$!**
- Still more precision needed: LHCb, TeVatron, Super-B $B_s \to J/\psi\eta^{(\prime)}$
- Do not use $Br(B_s \to D_s^{(*)+} D_s^{(*)-}) = \frac{\Delta\Gamma^{\rm CP}}{2\Gamma}$ - check size of 3-body FS!

b) $\tau_{B_s} = (1.001 \pm 0.014)\tau_{B_d}$: strong constraint on NP and duality violation
- Combine with other determinations of τ_{B_s}: LHCb, ATLAS?, CMS?
- B_s: Effective lifetimes, flavor specific lifetimes (2.x sigma deviation)
- $\tau_{\Lambda_b}, ...$

c) Di muon asymmetry A_{sl}^b
- HQE fails? **No! At most** $30 - 40\%$ — more precise test via $\tau(B_s), \Delta\Gamma_s, ...$
- NP acts in Γ_{12}? **No! At most** 40%**!** — More precise tests via $\tau(B_s), \Delta\Gamma_s, \Delta\Gamma_d, n_c, B_{sl}, r(0, 1, 2 \ \ \text{charm}), B_s \to \tau\tau, B \to K\tau\tau, ...$
- ???
- **Experimental cross-check via a_{sl}^d and a_{sl}^s!**

d) $\phi_s^{LHCb} \ll \phi_s^{A_{sl}^b}$ How large is the penguin pollution?
- Even small penguins can be important!
- **Values** for many penguin modes e.g. $B_s \to J/\psi K_s, K^0\bar{K}^0, \phi\phi, \eta^{(\prime)}\eta^{(\prime)}...$

What to do list - Theory

Test of HQE with lifetimes

- τ_{B+}/τ_{B_d} and τ_{B_s}/τ_{B_d} fits well $\Rightarrow$ currently no hints for deviations from HQE
- Precise non-perturbative matrix elements for 4-quark operators urgently needed
- Perturbative improvements of lifetime predictions

Theoretical predictions for mixing observables

- Precise decay constants and Bag parameter for ΔM
- Additional Bag parameters at dimension 6 and 7 for Γ_{12}
- α_s/m_b corrections for Γ_{12}
- α_s^2 corrections for Γ_{12}

Theoretical predictions for charm mixing observables

- Push HQE to its limits
- Try to imrove the exclusive approach

Update of theoretical predictions for inclusive rates - control penguins!!!

Moriond 2012: Conclusion from B-Mixing

It is actually not bad, what the Grinch left for us

Expansion in $1/m_b$ works so well,

What does this tell about charm? $1/m_c \approx 3 \cdot 1/m_b$

CKM$^-$: 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)

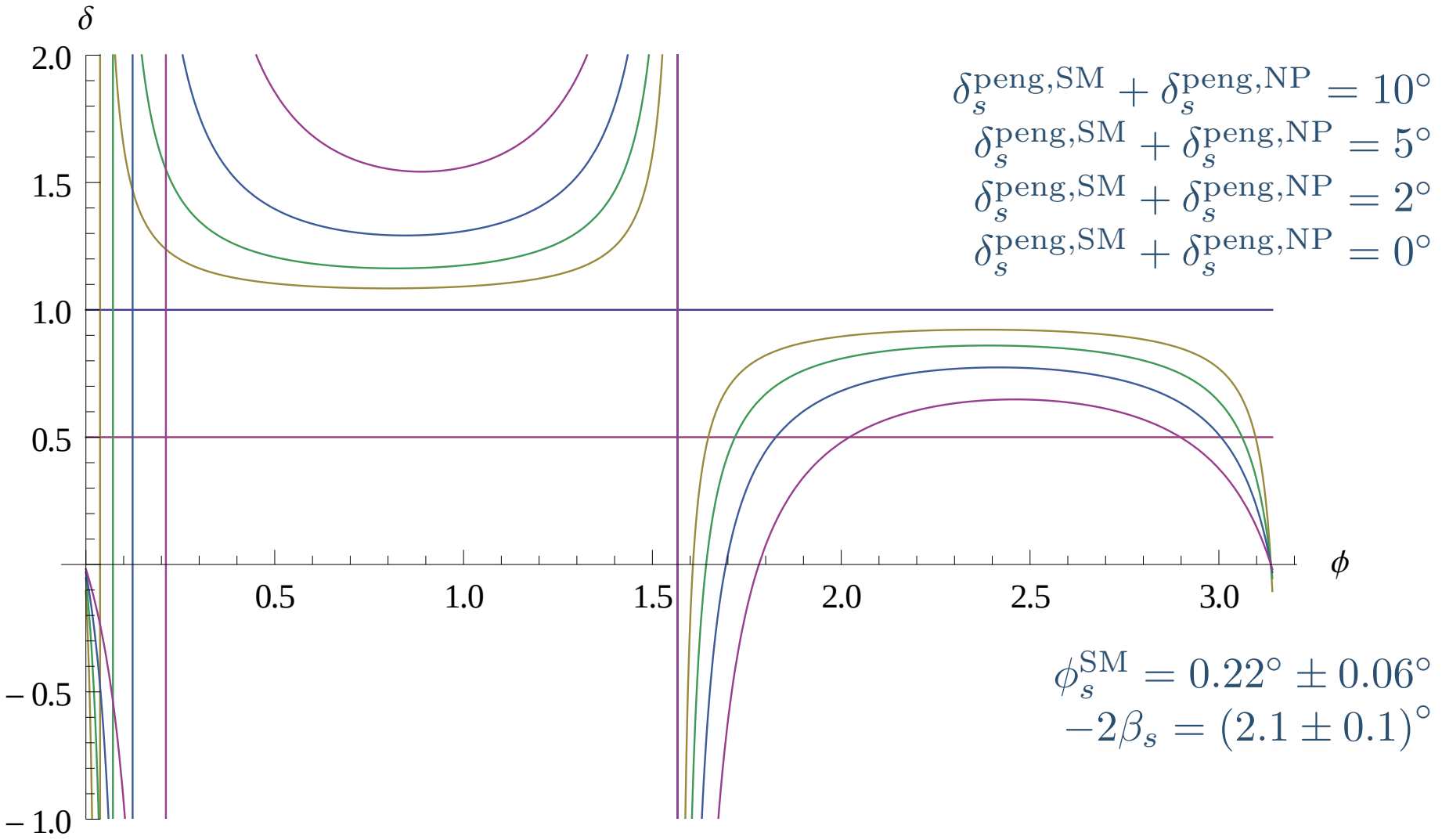
$$a_{sl}^s = -\frac{\Delta\Gamma}{\Delta M}\frac{S_{\psi\phi}}{\sqrt{1-S_{\psi\phi^2}}}\cdot\delta$$

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

CKM⁻: How large are Penguins? III



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

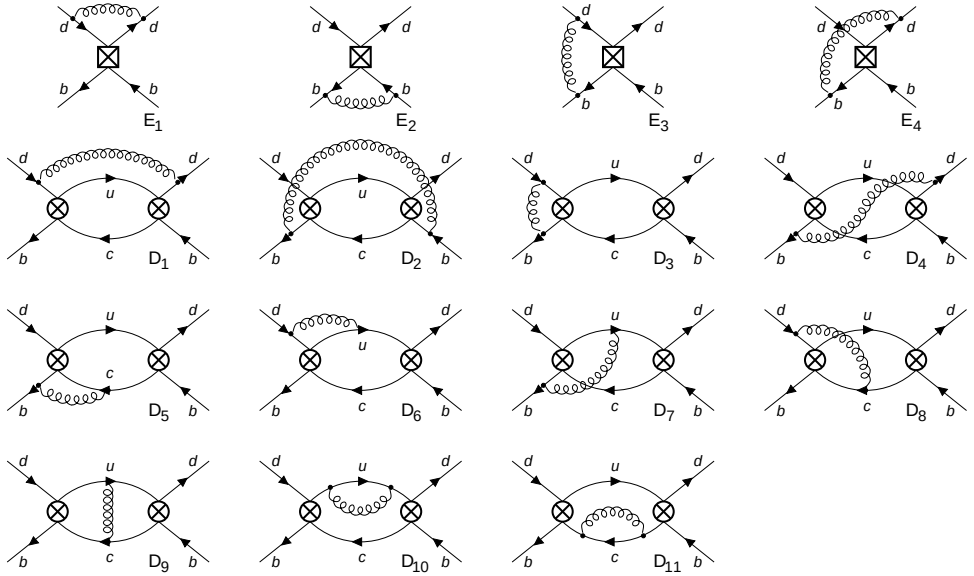
A.L. 1106.3200

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

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

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

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



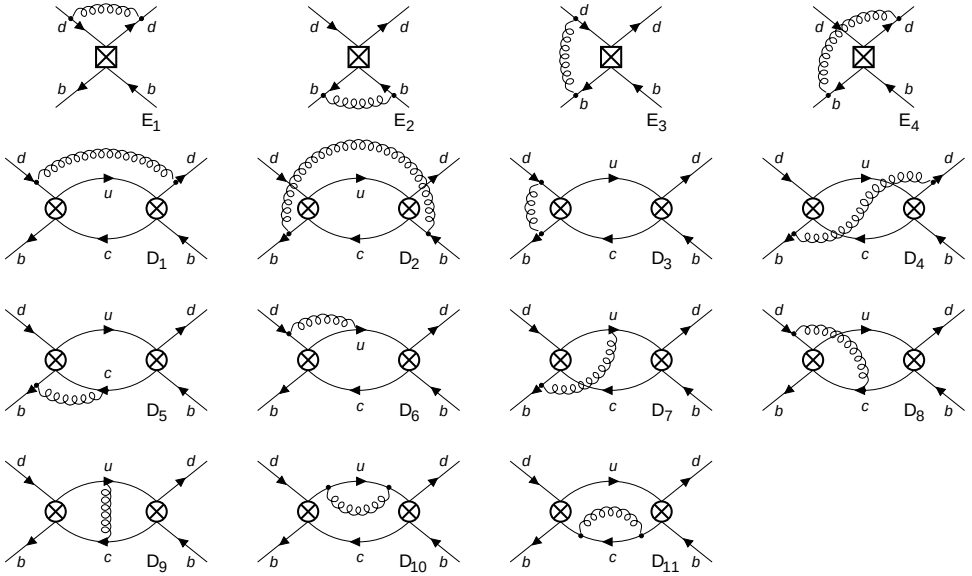
$$\left[\frac{\tau(B^+)}{\tau(B_d^0)}\right]_{\text{LO,NLO,HFAG10}} = 1.047 \pm 0.049 \leftrightarrow 1.063 \pm 0.027 \leftrightarrow 1.071 \pm 0.009$$

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.



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

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

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

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

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

Update urgently needed!

Lifetimes: Lifetimes of heavy hadrons

- $\tau(B^+)/\tau(B_d)$: HQE seems to fit, but we need urgently more precise hadronic matrix elements
-

$$\frac{\tau(B_s)}{\tau(B_d)} = 0.996...1.000 \quad \leftrightarrow \quad 0.969 \pm 0.017 \text{ HFAG 2011}$$

$$\text{A.L. 1102.4274} \quad \leftrightarrow \quad 1.004 \pm 0.018 \text{ LHCb-Conf2011-049}$$

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) neccessary

- $\tau(D)$, D-mixing: work in progress
  Bigi, Uraltsev 2001; Bobrowski, A.L., Riedl, Rohrwild 1002.4794; 1011.5608;
  Bobrowski, A.L. Nierste, Prill, to appear
  It is not unplausible that HQE might give reasonable estimates

Theory statements about CPV in D before LHCb

[1002.4794] How large can the SM contribution to CP violation in $D^0-\bar D^0$ mixing be? - Mozilla Firefox

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High Energy Physics - Phenomenology

How large can the SM contribution to CP violation in $D^0-\bar D^0$ mixing be?

M. Bobrowski, A. Lenz, J. Riedl, J. Rohrwild

(Submitted on 25 Feb 2010)

We investigate the maximum size of CP violating effects in D-mixing within the Standard Model (SM), using Heavy Quark Expansion (HQE) as theoretical working tool. For this purpose we determine the leading HQE contributions and also α_s corrections as well as subleading $1/m_c$ corrections to the absorptive part of the mixing amplitude of neutral D mesons. It turns out that these contributions to Γ_{12} do not vanish in the exact SU(3)_\mathrm{F} limit. Moreover, while the leading HQE terms give a result for Γ_{12} orders of magnitude lower than the current experimental value, we do find a sizeable phase. In the literature it was suggested that higher order terms in the HQE might be much less affected by the severe GIM cancellations of the leading terms; it is even not excluded that these higher order terms can reproduce the experimental value of y. If such an enhancement is realized in nature, the phase discovered in the leading HQE terms can have a sizeable effect. Therefore, we think that statements like: {\it "CP violating effects in D-mixing of the order of 10^{-3} to 10^{-2} are an unambigous sign of new physics"}--given our limited knowlegde of the SM prediction--are premature. Finally, we give an example of a new physics model that can enhance the leading HQE terms to Γ_{12} by one to two orders of magnitude.

Comments: 14 pages, considerably extended version of 0904.3971 with completely new main aspect; text (except title and abstract) identical to the version accepted by JHEP
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Experiment (hep-ex)
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