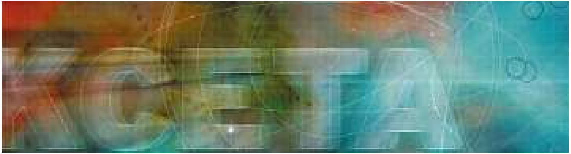
Flavour and CP Violation

Ulrich Nierste

Karlsruhe Institute of Technology

Karlsruhe Institute of Technology

Federal Ministry of Education and Research



Discrete 2012, IST Lisbon
Dec 3–7, 2012

Basics

SM Yukawa interaction:

Higgs doublet $H = \begin{pmatrix} G^+ \\ v + \frac{h^0 + iG^0}{\sqrt{2}} \end{pmatrix}$ with $v = 174\,\text{GeV}$.

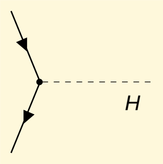
Charge-conjugate doublet: $\widetilde{H} = \begin{pmatrix} v + \frac{h^0 - iG^0}{\sqrt{2}} \\ -G^- \end{pmatrix}$

Basics

SM Yukawa interaction:

Higgs doublet $H = \begin{pmatrix} G^+ \\ v + \frac{h^0 + iG^0}{\sqrt{2}} \end{pmatrix}$ with $v = 174\,\text{GeV}$.

Charge-conjugate doublet: $\widetilde{H} = \begin{pmatrix} v + \frac{h^0 - iG^0}{\sqrt{2}} \\ -G^- \end{pmatrix}$



Yukawa lagrangian of quark fields:

$$-L_Y = Y^d_{jk}\, \overline{Q}^j_L\, H\, d^k_R \;+\; Y^u_{jk}\, \overline{Q}^j_L\, \widetilde{H}\, u^k_R \;+\; \text{h.c.}$$

with 3×3 matrices Yukawa matrices $Y^{u,d}$.

$\Rightarrow$ quark mass matrices $M^{u,d} = Y^{u,d} v$.

With three unphysical rotations achieve

$$Y^u = \widehat{Y}^u = \begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ 0 & 0 & y_t \end{pmatrix} \qquad \text{and} \qquad Y^d = V^\dagger \widehat{Y}^d$$

$$\text{with} \qquad \widehat{Y}^d = \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix}$$

and $y_i \geq 0$.

V is the unitary Cabbibbo-Kobayashi-Maskawa (CKM) matrix.

$$Y^u = \widehat{Y}^u = \begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ 0 & 0 & y_t \end{pmatrix}, \qquad Y^d = V^\dagger \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix}$$

$$Y^u = \widehat{Y}^u = \begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ 0 & 0 & y_t \end{pmatrix}, \qquad Y^d = V^\dagger \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix}$$

The last rotation

$$d_L^j = V_{jk} d_L^{k\prime}$$

diagonalises M^d, but puts V into the W boson vertices:

$$W_\mu \overline{u}_L^j \gamma^\mu d_L^j = W_\mu V_{jk} \overline{u}_L^j \gamma^\mu d_L^{k\prime}$$

Flavour physics is governed by extremely small numbers:

$$Y^d = V^\dagger \widehat{Y}^d = \begin{pmatrix} 10^{-5} & -7\cdot 10^{-5} & (12+6i)\cdot 10^{-5} \\ 4\cdot 10^{-6} & 3\cdot 10^{-4} & -6\cdot 10^{-4} \\ (2+6i)\cdot 10^{-8} & 10^{-5} & 2\cdot 10^{-2} \end{pmatrix}$$

evaluated at the energy scale m_t. Off-diagonal element with largest magnitude: $V_{ts}^* y_b \equiv V_{32}^* y_b = -6\cdot 10^{-4}$.

Flavour physics is governed by extremely small numbers:

$$Y^d = V^\dagger \widehat{Y}^d = \begin{pmatrix} 10^{-5} & -7\cdot 10^{-5} & (12+6i)\cdot 10^{-5} \\ 4\cdot 10^{-6} & 3\cdot 10^{-4} & -6\cdot 10^{-4} \\ (2+6i)\cdot 10^{-8} & 10^{-5} & 2\cdot 10^{-2} \end{pmatrix}$$

evaluated at the energy scale m_t. Off-diagonal element with largest magnitude: $V_{ts}^* y_b \equiv V_{32}^* y_b = -6 \cdot 10^{-4}$.

Flavour violation appears only in charged-current vertices. Flavour-changing neutral current (FCNC) processes are loop suppressed!

$\Rightarrow$ FCNC processes are sensitive to new physics.

Win-win situation

If ATLAS and CMS find particles not included in the SM:

Flavour physics will explore their couplings to quarks.

Win-win situation

If ATLAS and CMS find particles not included in the SM:

Flavour physics will explore their couplings to quarks.

If ATLAS and CMS find no new particles (apart from the SM Higgs boson):

Flavour physics probes scales of new physics exceeding 100 TeV.

Expand the CKM matrix V in $V_{us} \simeq \lambda = 0.2254$:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3\left(1+\frac{\lambda^2}{2}\right)(\overline{\rho}-i\overline{\eta}) \\ -\lambda-iA^2\lambda^5\overline{\eta} & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\overline{\rho}-i\overline{\eta}) & -A\lambda^2-iA\lambda^4\overline{\eta} & 1 \end{pmatrix}$$

with the Wolfenstein parameters λ, A, $\overline{\rho}$, $\overline{\eta}$

CP violation $\Leftrightarrow \overline{\eta} \neq 0$

Expand the CKM matrix V in $V_{us} \simeq \lambda = 0.2254$:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3\left(1+\frac{\lambda^2}{2}\right)(\overline{\rho}-i\overline{\eta}) \\ -\lambda-iA^2\lambda^5\overline{\eta} & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\overline{\rho}-i\overline{\eta}) & -A\lambda^2-iA\lambda^4\overline{\eta} & 1 \end{pmatrix}$$

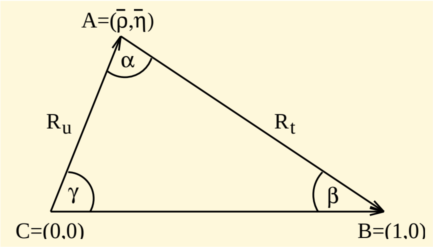
with the Wolfenstein parameters λ, A, $\overline{\rho}$, $\overline{\eta}$

CP violation $\Leftrightarrow \overline{\eta} \neq 0$

Unitarity triangle:

Exact definition:

$$\overline{\rho}+i\overline{\eta} = -\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} = \left|\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right| e^{i\gamma}$$



Neutral mesons

$$K \sim \bar{s}d, \qquad D \sim c\bar{u}, \qquad B_d \sim \bar{b}d, \qquad B_s \sim \bar{b}s,$$
$$\overline{K} \sim s\bar{d}, \qquad \overline{D} \sim \bar{c}u, \qquad \overline{B}_d \sim b\bar{d}, \qquad \overline{B}_s \sim b\bar{s},$$

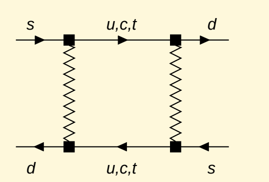
The neutral K, D, B_d and B_s mesons mix with their antiparticles, $\overline{K}$, $\overline{D}$, $\overline{B}_d$ and $\overline{B}_s$ thanks to the weak interaction (quantum-mechanical two-state systems).

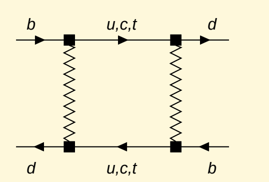
Neutral mesons

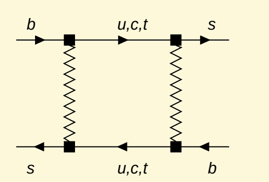
$$K \sim \overline{s}d, \qquad D \sim c\overline{u}, \qquad B_d \sim \overline{b}d, \qquad B_s \sim \overline{b}s,$$
$$\overline{K} \sim s\overline{d}, \qquad \overline{D} \sim \overline{c}u, \qquad \overline{B}_d \sim b\overline{d}, \qquad \overline{B}_s \sim b\overline{s},$$

The neutral K, D, B_d and B_s mesons mix with their antiparticles, $\overline{K}$, $\overline{D}$, $\overline{B}_d$ and $\overline{B}_s$ thanks to the weak interaction (quantum-mechanical two-state systems).

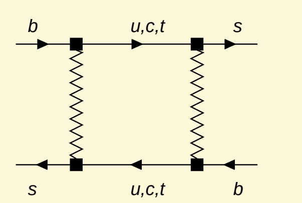
$\Rightarrow$ gold mine for new-physics searches





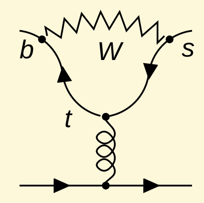


Compare FCNC processes:



$B_s - \overline{B}_s$ mixing

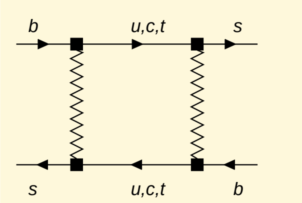
$|\Delta B| = 2$



penguin diagram

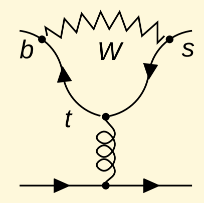
$|\Delta B| = 1$

Compare FCNC processes:



$B_s - \overline{B}_s$ mixing

$|\Delta B| = 2$



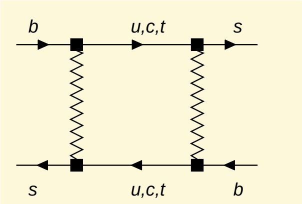
penguin diagram

$|\Delta B| = 1$

Sensitivity of $b \to s$ amplitude A to new physics with FCNC parameter $\delta_{\rm FCNC}$ and scale $\Lambda \gg M_W$:

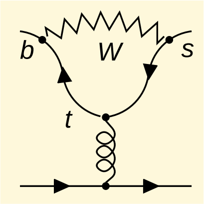
$$\frac{|A_{\rm NP}^{|\Delta B|=2}|}{|A_{\rm SM}^{|\Delta B|=2}|} = \frac{|\delta_{\rm FCNC}|^2}{|V_{ts}|^2} \frac{M_W^2}{\Lambda^2}, \qquad \frac{|A_{\rm NP}^{|\Delta B|=1}|}{|A_{\rm SM}^{|\Delta B|=1}|} = \frac{|\delta_{\rm FCNC}|}{|V_{ts}|} \frac{M_W^2}{\Lambda^2}.$$

Compare FCNC processes:



$B_s - \overline{B}_s$ mixing

$|\Delta B| = 2$



penguin diagram

$|\Delta B| = 1$

Sensitivity of $b \to s$ amplitude A to new physics with FCNC parameter $\delta_{\rm FCNC}$ and scale $\Lambda \gg M_W$:

$$\frac{|A_{\rm NP}^{|\Delta B|=2}|}{|A_{\rm SM}^{|\Delta B|=2}|} = \frac{|\delta_{\rm FCNC}|^2}{|V_{ts}|^2}\frac{M_W^2}{\Lambda^2}, \qquad \frac{|A_{\rm NP}^{|\Delta B|=1}|}{|A_{\rm SM}^{|\Delta B|=1}|} = \frac{|\delta_{\rm FCNC}|}{|V_{ts}|}\frac{M_W^2}{\Lambda^2}.$$

$\Rightarrow$ Meson-antimeson mixing is more sensitive to generic NP than FCNC decay amplitudes, if $|\delta_{\rm FCNC}| > |V_{ts}| \approx 0.04$.

$\mathrm{B}-\overline{\mathrm{B}}$ mixing in the Standard Model

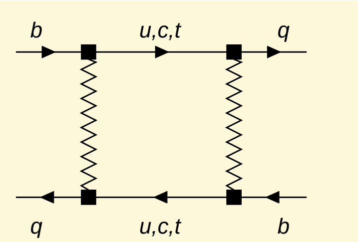
$\mathrm{B_q}-\overline{\mathrm{B}}_\mathrm{q}$ mixing with $q = d$ or $q = s$ involves the 2×2 matrices M and Γ.

$B-\overline{B}$ mixing in the Standard Model

$B_q-\overline{B}_q$ mixing with $q=d$ or $q=s$ involves the 2×2 matrices M and Γ.

The mass matrix element M_{12}^q stems from the dispersive (real) part of the box diagram, internal t.

The decay matrix element Γ_{12}^q stems from the absorpive (imaginary) part of the box diagram, internal c, u.

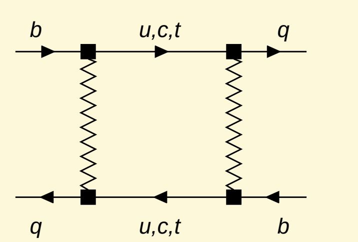


$\mathrm{B-\overline{B}}$ mixing in the Standard Model

$\mathrm{B_q-\overline{B}_q}$ mixing with $q = d$ or $q = s$ involves the 2×2 matrices M and Γ.

The mass matrix element M_{12}^q stems from the dispersive (real) part of the box diagram, internal t.

The decay matrix element Γ_{12}^q stems from the absorpive (imaginary) part of the box diagram, internal c, u.



3 physical quantities in $\mathrm{B_q-\overline{B}_q}$ mixing:

$$\left|M_{12}^q\right|, \quad \left|\Gamma_{12}^q\right|, \quad \phi_q \equiv \arg\left(-\frac{M_{12}^q}{\Gamma_{12}^q}\right)$$

The two eigenstates found by diagonalising $M - i\,\Gamma/2$ differ in their masses and widths:

$$\begin{aligned} \text{mass difference} \qquad \Delta m_q &\simeq 2|M_{12}^q|, \\ \text{width difference} \qquad \Delta \Gamma_q &\simeq 2|\Gamma_{12}^q| \cos\phi_q \end{aligned}$$

The two eigenstates found by diagonalising $M - i\,\Gamma/2$ differ in their masses and widths:

$$\begin{aligned} \text{mass difference} \qquad \Delta m_q &\simeq 2|M_{12}^q|, \\ \text{width difference} \qquad \Delta\Gamma_q &\simeq 2|\Gamma_{12}^q| \cos\phi_q \end{aligned}$$

CP asymmetry in flavour-specific decays (semileptonic CP asymmetry):

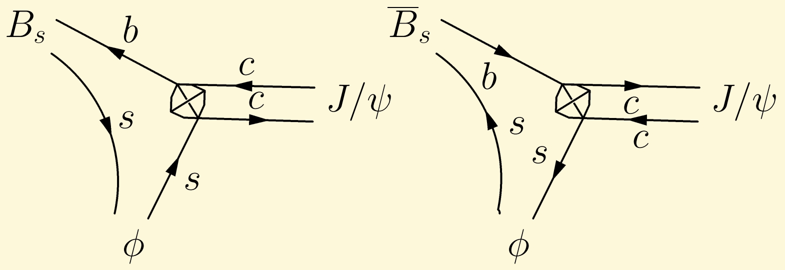
$$a_{\rm fs}^q = \frac{|\Gamma_{12}^q|}{|M_{12}^q|} \sin\phi_q$$

$B_s \to J/\psi\,\phi$

Angular momentum: $(J/\psi\,\phi)_{L=0,2}$: CP-even, $\eta_{CP} = 1$
$(J/\psi\,\phi)_{L=1}$: CP-odd, $\eta_{CP} = -1$

Time-dependent CP asymmetry:

$$a_{CP}(t) = \frac{\Gamma(B_s(t) \to (J/\psi\,\phi)_L) - \Gamma(\bar{B}_s(t) \to (J/\psi\,\phi)_L)}{\Gamma(B_s(t) \to (J/\psi\,\phi)_L) + \Gamma(\bar{B}_s(t) \to (J/\psi\,\phi)_L)}$$



Time-dependent CP asymmetry in $B_s(t) \to (J/\psi\, \phi)_L$:

$$a_{CP}(t) = \eta_{CP} \frac{\sin(2\beta_s)\sin(\Delta m_s t)}{\cosh(\Delta\Gamma_s t/2) - \cos(2\beta_s)\sinh(\Delta\Gamma_s t/2)}$$

Standard Model prediction from a global fit to UT:

$$\sin(2\beta_s) \simeq 2\lambda^2\overline{\eta} = 0.036 \pm 0.003 \quad @95\%CL,$$

CKMfitter Sep 2012,

so that $2\beta_s = 2.1^\circ \pm 0.2^\circ$.

In $a_{CP}(t)$ the penguin pollution is neglected, it may affect the extraction of $2\beta_s$ from $a_{CP}(t)$ by $\mathcal{O}(1^\circ)$.

LHCb full 2011 data set:

$$2\beta_s^{\rm exp} = 0.002 \pm 0.083_{\rm stat} \pm 0.027_{\rm syst}$$

$$= 0.1^\circ \pm 4.8^\circ_{\rm stat} \pm 1.5^\circ_{\rm syst}$$

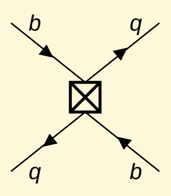
from $B_s \to J/\psi\phi$ and $B_s \to J/\psi\pi\pi$.

LHCb-CDF-DØ average

$$2\beta_s^{\rm exp} = 0.044^{+0.090}_{-0.085} = 2.5^{\circ}{}^{+5.2^\circ}_{-4.9^\circ} \qquad \text{HFAG 2012}$$

in good agreement with the SM expectation $2\beta_s = 2.1^\circ \pm 0.2^\circ$.

Δm_s and Δm_d



Operator Product Expansion:

$$M_{12}^q = |V_{tq}^* V_{tb}|^2 \, C Q$$

Local Operator:

$$Q \;=\; \overline{q}_L \gamma_\nu b_L \, \overline{q}_L \gamma^\nu b_L$$

Theoretical uncertainty of Δm_q dominated by matrix element:

$$\langle \mathrm{B_q} | Q | \overline{\mathrm{B}}_q \rangle \;=\; \frac{2}{3} M_{B_q}^2 \, f_{B_q}^2 \, B_{B_q}$$

Standard Model: $C = C(m_t, \alpha_s)$ is well-known.

Δm_s

$B_s - \overline{B}_s$ mixing: CKM unitarity fixes $|V_{ts}| \simeq |V_{cb}|$. Use lattice results for $f_{B_q}^2 \, B_{B_q}$ to confront $\Delta m_s^{\rm exp}$ with the Standard Model:

$$\Delta m_s = \left(18.8 \pm 0.6_{\,V_{cb}} \pm 0.3_{\,m_t} \pm 0.1_{\,\alpha_s} \right) \text{ps}^{-1} \, \frac{f_{B_s}^2 \, B_{B_s}}{(220\,\text{MeV})^2}$$

Here $\overline{\rm MS}$-NDR scheme for B_{B_q} at scale m_b.

Often used: scheme-invariant $\widehat{B}_{B_q} = 1.51 B_{B_q}$.

Recall:

$$\Delta m_s = \left(18.8 \pm 0.6_{V_{cb}} \pm 0.3_{m_t} \pm 0.1_{\alpha_s} \right) \text{ps}^{-1} \frac{f_{B_s}^2 B_{B_s}}{(220\,\text{MeV})^2}$$

CKMfitter lattice averages (1203.0238):

$$f_{B_s} = (229 \pm 2 \pm 6)\,\text{MeV}, \qquad B_{B_s} = 0.85 \pm 0.02 \pm 0.02$$

means $f_{B_s}^2 B_{B_s} = (211 \pm 9)\,\text{MeV}$ and

$$\Delta m_s = (17.3 \pm 1.5)\,\text{ps}^{-1}$$

complying with LHCb/CDF average

$$\Delta m_s^{\text{exp}} = (17.731 \pm 0.045)\,\text{ps}^{-1}$$

$\Delta m_s = (17.3 \pm 1.5)\,\mathrm{ps}^{-1}$ versus
$\Delta m_s^{\mathrm{exp}} = (17.731 \pm 0.045)\,\mathrm{ps}^{-1}$, too good to be true...

$\Delta m_s = (17.3 \pm 1.5)\,\text{ps}^{-1}$ versus
$\Delta m_s^{\text{exp}} = (17.731 \pm 0.045)\,\text{ps}^{-1}$, too good to be true...

Few lattice-QCD calculations of $f_{B_s}^2 B_{B_s}$ available!

Prediction of Δm_s largely relies on calculations of f_{B_s} and the prejudice $B_{B_s} \simeq 0.85$.

With recent preliminary Fermilab/MILC result (1112.5642),

$$f_{B_s}^2\, B_{B_s} = 0.0559(68)\,\mathrm{GeV}^2 \simeq [(237 \pm 14)\,\mathrm{MeV}]^2\,,$$

one finds

$$\Delta m_s = (21.7 \pm 2.6)\,\mathrm{ps}^{-1}$$

Decay matrix

The calculation Γ_{12}^q, $q = d, s$, is needed for

the width difference $\Delta\Gamma_q \simeq 2|\Gamma_{12}^q| \cos\phi_q$

and the semileptonic CP asymmetry $a_{\rm fs}^q = \frac{|\Gamma_{12}^q|}{|M_{12}^q|} \sin\phi_q$

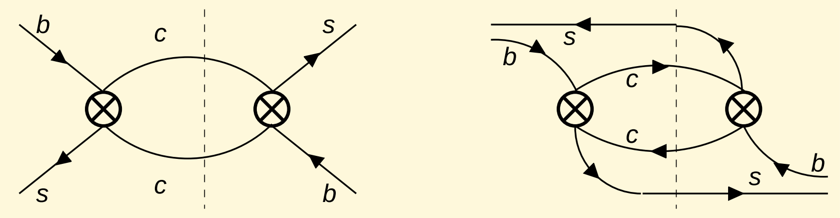
In the Standard Model

$$\phi_s = 0.22^\circ \pm 0.06^\circ \quad \text{and} \quad \phi_d = -4.3^\circ \pm 1.4^\circ.$$

Recalling $\phi_q = \arg\left(-\frac{M_{12}^q}{\Gamma_{12}^q}\right)$, a new physics contribution to $\arg M_{12}^q$ may deplete $\Delta\Gamma_q$ and enhance $|a_{\rm fs}^q|$ to a level observable at current experiments.

But: Precise data on CP violation in $B_d \to J/\psi K_S$ and $B_s \to J/\psi\phi$ preclude large NP contributions to $\arg\phi_d$ and $\arg\phi_s$.

Leading contribution to Γ_{12}^{s}:



Γ_{12}^{s} stems from Cabibbo-favoured tree-level $b \to c\bar{c}s$ decays, sizable new-physics contributions are impossible.

Updated Standard-Model prediction for $\Delta\Gamma_s/\Delta m_s$ in terms of hadronic parameters:

$$\frac{\Delta\Gamma_s}{\Delta m_s}\Delta m_s^{\rm exp} = \left[0.082 + 0.019\frac{\widetilde{B}'_{S,B_s}}{B_{B_s}} - 0.025\frac{B_R}{B_{B_s}}\right] \text{ps}^{-1}$$

Here

$$\langle B_s|\overline{s}_L^{\alpha} b_R^{\beta}\, \overline{s}_L^{\beta} b_R^{\alpha}|\overline{B}_s\rangle = \frac{1}{12} M_{B_s}^2\, f_{B_s}^2\, \widetilde{B}'_{S,B_s}$$

and $B_R = 1 \pm 0.5$ parametrises the size of higher-dimension operators.

With preliminary Fermilab/MILC result (1112.5642),

$$\frac{\widetilde{B}'_{S,B_s}}{B_{B_S}} = 1.23 \pm 0.24$$

find:

$$\frac{\Delta\Gamma_s}{\Delta m_s}\Delta m^{\rm exp} = \left[0.075 \pm 0.015_{B_R/B} \pm 0.012_{\rm scale} \pm 0.004_{\widetilde{B}/B}\right] \text{ps}^{-1}$$

complies well with LHCb-CDF-DØ average

$$\Delta\Gamma_s = [0.105 \pm 0.015]\,\text{ps}^{-1} \qquad \text{HFAG 2012}$$

New physics

M_{12}^{s} is highly sensitive to new physics, unlike the tree-level decay $b \to c\bar{c}s$ responsible for $B_s \to J/\psi\phi$ and Γ_{12}^{s}.

It is plausible to consider a generic scenario, in which the M_{12} elements in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$, $\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$, and $\mathrm{K}-\overline{\mathrm{K}}$ mixing are affected by new-physics, while all other quantities entering the global fit to the UT are as in the Standard-Model.

New physics

Trouble maker:

$$
\begin{aligned}
A_{\mathrm{SL}} &= (0.532 \pm 0.039) a_{\mathrm{fs}}^{d} + (0.468 \pm 0.039) a_{\mathrm{fs}}^{s} \\
&= (-7.87 \pm 1.72 \pm 0.93) \cdot 10^{-3} \qquad \text{DØ 2011}
\end{aligned}
$$

This is 3.9σ away from $a_{\mathrm{fs}}^{\mathrm{SM}} = (-0.24 \pm 0.03) \cdot 10^{-3}$.

A. Lenz, UN 2006,2011

New physics

Trouble maker:

$$A_{\rm SL} = (0.532 \pm 0.039) a_{\rm fs}^d + (0.468 \pm 0.039) a_{\rm fs}^s$$
$$= (-7.87 \pm 1.72 \pm 0.93) \cdot 10^{-3} \qquad \text{DØ 2011}$$

This is 3.9σ away from $a_{\rm fs}^{\rm SM} = (-0.24 \pm 0.03) \cdot 10^{-3}$.

A. Lenz, UN 2006,2011

Define the complex parameters Δ_d and Δ_s through

$$M_{12}^q \equiv M_{12}^{\rm SM,q} \cdot \Delta_q\,, \qquad \Delta_q \equiv |\Delta_q| e^{i\phi_q^\Delta}.$$

In the Standard Model $\Delta_q = 1$. Use $\phi_s = \phi_s^{\rm SM} + \phi_s^\Delta \simeq \phi_s^\Delta$.

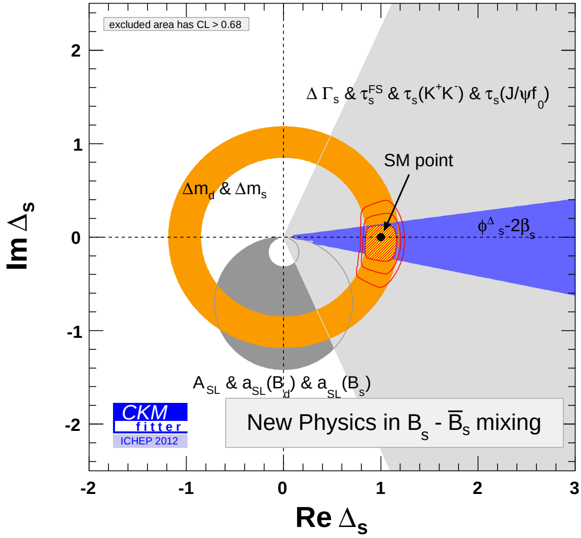
Global analysis of $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing and $\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ mixing with
A. Lenz and the CKMfitter Group (J. Charles,
S. Descotes-Genon, A. Jantsch, C. Kaufhold, H. Lacker,
S. Monteil, V. Niess) arXiv:1008.1593, 1203.0238

Rfit method: No statistical meaning is assigned to systematic errors and theoretical uncertainties.

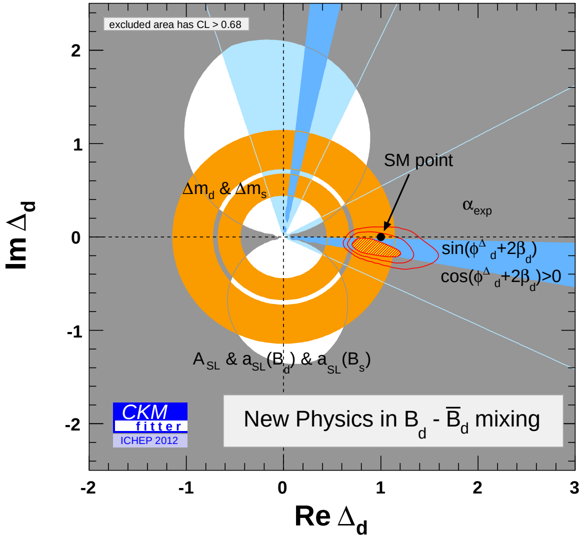
We have performed a simultaneous fit to the Wolfenstein parameters and to the new physics parameters Δ_s and Δ_d:

$$\Delta_q \equiv \frac{M_{12}^q}{M_{12}^{q,\mathrm{SM}}}, \qquad \Delta_q \equiv |\Delta_q| e^{i\phi_q^\Delta}.$$

CKMfitter September 2012 update of 1203.0238:



CKMfitter September 2012 update of 1203.0238:



$A_{\rm SL}$ and WA for $B(B \to \tau\nu)$ prefer small $\phi_d^\Delta < 0$.

Pull value for A_{SL}: 3.3σ

$\Rightarrow$ Scenario with NP in M_{12}^{q} only cannot accomodate the DØ measurement of A_{SL}.

The Standard Model point $\Delta_s = \Delta_d = 1$ is disfavoured by 1σ, down from the 2010 value of 3.6σ.

New physics in Γ_{12}^q?

The LHCb measurement of Γ_s implies

$$\frac{\Gamma_d}{\Gamma_s} = \frac{\tau_{B_s}}{\tau_{B_d}} = 0.997 \pm 0.013$$

in excellent agreement with the SM prediction
$\tau_{B_s}/\tau_{B_d} = 0.998 \pm 0.003$.
Changing the Cabibbo-favoured tree-level quantity $|\Gamma_{12}^s|$ by opening new enhanced decay channels such as $B_s \to \tau^+\tau^-$ will spoil this ratio.

New physics in Γ_{12}^q?

The LHCb measurement of Γ_s implies

$$\frac{\Gamma_d}{\Gamma_s} = \frac{\tau_{B_s}}{\tau_{B_d}} = 0.997 \pm 0.013$$

in excellent agreement with the SM prediction
$\tau_{B_s}/\tau_{B_d} = 0.998 \pm 0.003$.
Changing the Cabibbo-favoured tree-level quantity $|\Gamma_{12}^s|$ by opening new enhanced decay channels such as $B_s \to \tau^+\tau^-$ will spoil this ratio.

Phenomenologically, new physics in the doubly Cabibbo-suppressed quantity Γ_{12}^d is still allowed, but requires somewhat contrived models of new physics.

Supersymmetry

The MSSM has many new sources of flavour violation, all in the supersymmetry-breaking sector.

No problem to get a big effect in a given FCNC process, but rather to suppress big effects elsewhere (supersymmetric flavour problem).

With squark masses well beyond 1 TeV the supersymmetric flavour problem is substantially alleviated.

Squark mass matrix

Diagonalise the Yukawa matrices Y^u_{jk} and Y^d_{jk}

$\Rightarrow$ quark mass matrices are diagonal, super-CKM basis

Squark mass matrix

Diagonalise the Yukawa matrices Y^u_{jk} and Y^d_{jk}
$\Rightarrow$ quark mass matrices are diagonal, super-CKM basis
E.g. Down-squark mass matrix:

$$M^2_{\tilde{d}} = \begin{pmatrix} \left(M^{\tilde{d}}_{1L}\right)^2 & \Delta^{\tilde{d}\,LL}_{12} & \Delta^{\tilde{d}\,LL}_{13} & \Delta^{\tilde{d}\,LR}_{11} & \Delta^{\tilde{d}\,LR}_{12} & \Delta^{\tilde{d}\,LR}_{13} \\ \Delta^{\tilde{d}\,LL\,*}_{12} & \left(M^{\tilde{d}}_{2L}\right)^2 & \Delta^{\tilde{d}\,LL}_{23} & \Delta^{\tilde{d}\,RL\,*}_{12} & \Delta^{\tilde{d}\,LR}_{22} & \Delta^{\tilde{d}\,LR}_{23} \\ \Delta^{\tilde{d}\,LL\,*}_{13} & \Delta^{\tilde{d}\,LL\,*}_{23} & \left(M^{\tilde{d}}_{3L}\right)^2 & \Delta^{\tilde{d}RL\,*}_{13} & \Delta^{\tilde{d}\,RL*}_{23} & \Delta^{\tilde{d}\,LR}_{33} \\ \Delta^{\tilde{d}\,LR\,*}_{11} & \Delta^{\tilde{d}RL}_{12} & \Delta^{\tilde{d}RL}_{13} & \left(M^{\tilde{d}}_{1R}\right)^2 & \Delta^{\tilde{d}\,RR}_{12} & \Delta^{\tilde{d}\,RR}_{13} \\ \Delta^{\tilde{d}\,LR\,*}_{12} & \Delta^{\tilde{d}\,LR*}_{22} & \Delta^{\tilde{d}RL}_{23} & \Delta^{\tilde{d}\,RR\,*}_{12} & \left(M^{\tilde{d}}_{2R}\right)^2 & \Delta^{\tilde{d}\,RR}_{23} \\ \Delta^{\tilde{d}\,LR\,*}_{13} & \Delta^{\tilde{d}\,LR\,*}_{23} & \Delta^{\tilde{d}\,LR\,*}_{33} & \Delta^{\tilde{d}\,RR\,*}_{13} & \Delta^{\tilde{d}\,RR\,*}_{23} & \left(M^{\tilde{d}}_{3R}\right)^2 \end{pmatrix}$$

Squark mass matrix

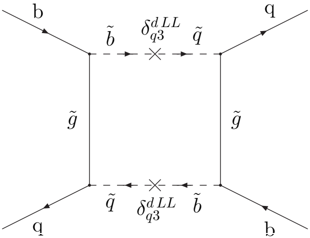
Diagonalise the Yukawa matrices Y^u_{jk} and Y^d_{jk}

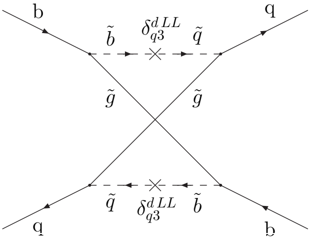
$\Rightarrow$ quark mass matrices are diagonal, super-CKM basis

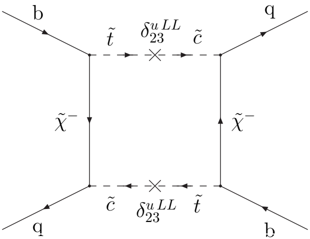
E.g. Down-squark mass matrix:

$$M^2_{\tilde{d}} = \begin{pmatrix} \left(M^{\tilde{d}}_{1L}\right)^2 & \Delta^{\tilde{d}\,LL}_{12} & \Delta^{\tilde{d}\,LL}_{13} & \Delta^{\tilde{d}\,LR}_{11} & \Delta^{\tilde{d}\,LR}_{12} & \Delta^{\tilde{d}\,LR}_{13} \\ \Delta^{\tilde{d}\,LL}_{12}{}^{*} & \left(M^{\tilde{d}}_{2L}\right)^2 & \Delta^{\tilde{d}\,LL}_{23} & \Delta^{\tilde{d}\,RL}_{12}{}^{*} & \Delta^{\tilde{d}\,LR}_{22} & \Delta^{\tilde{d}\,LR}_{23} \\ \Delta^{\tilde{d}\,LL}_{13}{}^{*} & \Delta^{\tilde{d}\,LL}_{23}{}^{*} & \left(M^{\tilde{d}}_{3L}\right)^2 & \Delta^{\tilde{d}RL}_{13}{}^{*} & \Delta^{\tilde{d}\,RL*}_{23} & \Delta^{\tilde{d}\,LR}_{33} \\ \Delta^{\tilde{d}\,LR}_{11}{}^{*} & \Delta^{\tilde{d}RL}_{12} & \Delta^{\tilde{d}RL}_{13} & \left(M^{\tilde{d}}_{1R}\right)^2 & \Delta^{\tilde{d}\,RR}_{12} & \Delta^{\tilde{d}\,RR}_{13} \\ \Delta^{\tilde{d}\,LR}_{12}{}^{*} & \Delta^{\tilde{d}\,LR*}_{22} & \Delta^{\tilde{d}RL}_{23} & \Delta^{\tilde{d}\,RR}_{12}{}^{*} & \left(M^{\tilde{d}}_{2R}\right)^2 & \Delta^{\tilde{d}\,RR}_{23} \\ \Delta^{\tilde{d}\,LR}_{13}{}^{*} & \Delta^{\tilde{d}\,LR}_{23}{}^{*} & \Delta^{\tilde{d}\,LR}_{33}{}^{*} & \Delta^{\tilde{d}\,RR}_{13}{}^{*} & \Delta^{\tilde{d}\,RR}_{23}{}^{*} & \left(M^{\tilde{d}}_{3R}\right)^2 \end{pmatrix}$$

Not diagonal! $\Rightarrow$ new FCNC transitions.







$$\delta_{ij}^{q\,LL} = \frac{\Delta_{ij}^{\tilde{q}\,LL}}{\frac{1}{6}\sum_s M_{\tilde{q},ss}^2}, \qquad q=u,d$$

Flavour and SUSY GUT

Linking quarks to neutrinos: Flavour mixing:
quarks: Cabibbo-Kobayashi-Maskawa (CKM) matrix
leptons: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

Consider SU(5) multiplets:

$$\overline{\mathbf{5}}_1 = \begin{pmatrix} d_R^c \\ d_R^c \\ d_R^c \\ e_L \\ -\nu_e \end{pmatrix}, \qquad \overline{\mathbf{5}}_2 = \begin{pmatrix} s_R^c \\ s_R^c \\ s_R^c \\ \mu_L \\ -\nu_\mu \end{pmatrix}, \qquad \overline{\mathbf{5}}_3 = \begin{pmatrix} b_R^c \\ b_R^c \\ b_R^c \\ \tau_L \\ -\nu_\tau \end{pmatrix}.$$

If the observed large atmospheric neutrino mixing angle stems from a rotation of $\overline{\mathbf{5}}_2$ and $\overline{\mathbf{5}}_3$, it will induce a large $\tilde{b}_R - \tilde{s}_R$-mixing (Moroi; Chang,Masiero,Murayama).

$\Rightarrow$ new b_R–s_R transitions from gluino–squark loops possible.

Key ingredients: Some weak basis with

$$\mathsf{Y}_d = V_{\mathrm{CKM}}^{*} \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix} U_{\mathrm{PMNS}}$$

and right-handed down squark mass matrix:

$$\mathsf{m}_{\tilde{d}}^2 (M_Z) = \mathrm{diag} \left(m_{\tilde{d}}^2, m_{\tilde{d}}^2, m_{\tilde{d}}^2 - \Delta_{\tilde{d}} \right).$$

with a calculable real parameter $\Delta_{\tilde{d}}$, typically generated by top-Yukawa RG effects.

Rotating Y_d to diagonal form puts the large atmospheric neutrino mixing angle into $m^2_{\tilde{d}}$:

$$U^\dagger_{\mathrm{PMNS}}\, m^2_{\tilde{d}}\, U_{\mathrm{PMNS}} = \begin{pmatrix} m^2_{\tilde{d}} & 0 & 0 \\ 0 & m^2_{\tilde{d}} - \frac{1}{2}\,\Delta_{\tilde{d}} & -\frac{1}{2}\,\Delta_{\tilde{d}}\, e^{i\xi} \\ 0 & -\frac{1}{2}\,\Delta_{\tilde{d}}\, e^{-i\xi} & m^2_{\tilde{d}} - \frac{1}{2}\,\Delta_{\tilde{d}} \end{pmatrix}$$

The CP phase ξ affects CP violation in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing!

The Chang–Masiero–Murayama (CMM) model is based on the symmetry breaking chain

$SO(10) \to SU(5) \to SU(3) \times SU(2)_L \times U(1)_Y$.

The Chang–Masiero–Murayama (CMM) model is based on the symmetry breaking chain

$SO(10) \rightarrow SU(5) \rightarrow SU(3) \times SU(2)_L \times U(1)_Y$.

SO(10) superpotential:

$$
\begin{aligned}
W_Y &= \frac{1}{2} 16_i \, Y_u^{ij} \, 16_j \, 10_H + \frac{1}{2} 16_i \, Y_d^{ij} \, 16_j \, \frac{45_H \, 10'_H}{M_{Pl}} \\
&+ \frac{1}{2} 16_i \, Y_N^{ij} \, 16_j \, \frac{\overline{16}_H \overline{16}_H}{M_{Pl}}
\end{aligned}
$$

with the Planck mass M_{Pl} and

- 16_i: one matter superfield per generation, $i = 1, 2, 3$,
- 10_H: Higgs superfield containing MSSM Higgs superfield H_u,
- $10'_H$: Higgs superfield containing MSSM superfield H_u,
- 45_H: Higgs superfield in adjoint representation,
- $\overline{16}_H$: Higgs superfield in spinor representation.

"Most minimal flavour violation"

The Yukawa matrices Y_u and Y_N are always symmetric. In the CMM model they are assumed to be simultaneously diagonalisable at the scale M_{Pl}, where the soft SUSY-breaking terms are universal.

Realistic GUTs involve further dimension-5 Yukawa terms to fix the Yukawa unification in the first two generations. One can use these terms to shuffle a part of the effect from $b_R \to s_R$ into $b_R \to d_R$ transitions. This “leakage” is strongly constrained by $\mathrm{K}-\overline{\mathrm{K}}$ mixing. Trine,Wiesenfeldt,Westhoff 2009

Realistic GUTs involve further dimension-5 Yukawa terms to fix the Yukawa unification in the first two generations. One can use these terms to shuffle a part of the effect from $b_R \to s_R$ into $b_R \to d_R$ transitions. This “leakage” is strongly constrained by $K-\overline{K}$ mixing. Trine,Wiesenfeldt,Westhoff 2009

Similar constraints can be found from $\mu \to e\gamma$.

Ko,Park,Yamaguchi 2008; Borzumati,Yamashita 2009;

Girrbach,Mertens,UN,Wiesenfeldt 2009.

Chang-Masiero-Murayama model

We have considered $B_s - \overline{B}_s$ mixing, $b \to s\gamma$, $\tau \to \mu\gamma$, vacuum stability bounds, lower bounds on sparticle masses and the mass of the lightest Higgs boson.
The analysis involves 7 parameters in addition to those of the Standard Model.

Generic results: Largest effects in $B_s - \overline{B}_s$ mixing, $\tau \to \mu\gamma$
tension with M_h

J. Girrbach, S. Jäger, M. Knopf, W. Martens, UN, C. Scherrer, S. Wiesenfeldt
1101.6047

Methodology:

Input:

- squark masses $M_{\tilde{u}}$, $M_{\tilde{d}}$ of right-handed up and down squarks,
- trilinear term a_1^d of first generation,
- gluino mass $m_{\tilde{g}_3}$,
- $\arg \mu$,
- $\tan \beta$

Methodology:

Input:

- squark masses $M_{\tilde{u}}$, $M_{\tilde{d}}$ of right-handed up and down squarks,
- trilinear term a_1^d of first generation,
- gluino mass $m_{\tilde{g}_3}$,
- $\arg\mu$,
- $\tan\beta$

RG evolution from $M_{\rm ew}$ to $M_{\rm Pl}$: find universal soft terms a_0, m_0, $m_{\tilde{g}}$ and D.

Methodology:

Input:

- squark masses $M_{\tilde{u}}$, $M_{\tilde{d}}$ of right-handed up and down squarks,
- trilinear term a_1^d of first generation,
- gluino mass $m_{\tilde{g}_3}$,
- arg μ,
- tan β

RG evolution from $M_{\rm ew}$ to $M_{\rm Pl}$: find universal soft terms a_0, m_0, $m_{\tilde{g}}$ and D.

RG evolution back to $M_{\rm ew}$: calculate $|\mu|$ from electroweak symmetry breaking

Methodology:

Input:

- squark masses $M_{\tilde{u}}$, $M_{\tilde{d}}$ of right-handed up and down squarks,
- trilinear term a_1^d of first generation,
- gluino mass $m_{\tilde{g}_3}$,
- arg μ,
- tan β

RG evolution from $M_{\rm ew}$ to $M_{\rm Pl}$: find universal soft terms a_0, m_0, $m_{\tilde{g}}$ and D.

RG evolution back to $M_{\rm ew}$: calculate $|\mu|$ from electroweak symmetry breaking

Repeat RG evolution $M_{\rm ew} \to M_{\rm Pl} \to M_{\rm ew}$: find all particle masses and MSSM couplings

Methodology:

Input:

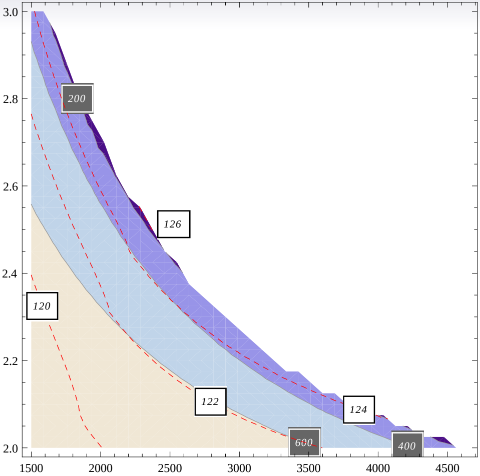
- squark masses $M_{\tilde{u}}$, $M_{\tilde{d}}$ of right-handed up and down squarks,
- trilinear term a_1^d of first generation,
- gluino mass $m_{\tilde{g}_3}$,
- arg μ,
- $\tan\beta$

RG evolution from $M_{\rm ew}$ to $M_{\rm Pl}$: find universal soft terms a_0, m_0, $m_{\tilde{g}}$ and D.

RG evolution back to $M_{\rm ew}$: calculate $|\mu|$ from electroweak symmetry breaking

Repeat RG evolution $M_{\rm ew} \to M_{\rm Pl} \to M_{\rm ew}$: find all particle masses and MSSM couplings

adjust CP phase ξ to approximate experimental Δ_s best.

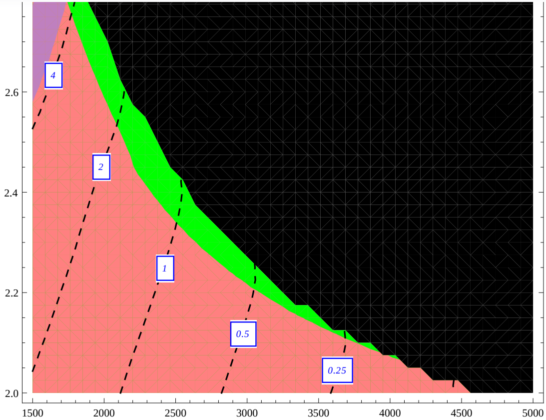


J. Stöckel, UN, work in progress:

$m_{\tilde{g}_3} = 1100\,\text{GeV}$,
$\mu > 0$, $\tan\beta = 10$

White: too light top squark
Red dashed lines:
Higgs mass (white labels)
Gray labels:
mass of lightest stop

x-axis: first-generation squark mass $M_{\tilde{q}}$ in GeV
y-axis: $a_1^d / M_{\tilde{q}}$



$m_{\tilde{g}_3} = 1100\,\text{GeV}$,
$\mu > 0$, $\tan\beta = 10$

Black: too light top squark
Red: forbidden my M_h
Violet: forbidden by
$Br(\tau \to \mu\gamma)$
Black dashed lines:
$10^8 \cdot Br(\tau \to \mu\gamma)$
(white labels)

x-axis: first-generation squark mass $M_{\tilde{q}}$ in GeV
y-axis: $a_1^d / M_{\tilde{q}}$

Conclusions

- Δm_s and $\Delta\Gamma_s$ comply with the Standard-Model expectation, but better lattice data are needed.

Conclusions

- Δm_s and $\Delta\Gamma_s$ comply with the Standard-Model expectation, but better lattice data are needed.
- Scenarios with new physics only in $M_{12}^{d,s}$ can only marginally improve A_{SL}, through $\phi_{d,s}^{\Delta} < 0$.

Conclusions

- Δm_s and $\Delta\Gamma_s$ comply with the Standard-Model expectation, but better lattice data are needed.
- Scenarios with new physics only in $M_{12}^{d,s}$ can only marginally improve A_{SL}, through $\phi_{d,s}^{\Delta} < 0$.
- New physics in Γ_{12}^{s} from yet undiscovered B_s decay modes is not viable, but maybe new physics in Γ_{12}^{d} is worthwhile to look at.

Conclusions

- Δm_s and $\Delta\Gamma_s$ comply with the Standard-Model expectation, but better lattice data are needed.
- Scenarios with new physics only in $M_{12}^{d,s}$ can only marginally improve A_{SL}, through $\phi_{d,s}^{\Delta} < 0$.
- New physics in Γ_{12}^s from yet undiscovered B_s decay modes is not viable, but maybe new physics in Γ_{12}^d is worthwhile to look at.
- Models of GUT flavour physics with $\tilde{b} \to \tilde{s}$ transitions driven by the atmospheric neutrino mixing angle could affect $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing without conflicting with $b \to s\gamma$ and $\tau \to \mu\gamma$, while accomodating $M_h = 126\,\mathrm{GeV}$.