B mixing and supersymmetry

Ulrich Nierste

Karlsruhe Institute of Technology

Theory seminar
Fermilab, July 2011

May 17, 2010

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July 9, 2011

New Scientist:

> *“This result won’t explain all of the matter-antimatter asymmetry,” says Val Gibson at the University of Cambridge,“but it could indicate new physics.” ....*
> *“‘Supersymmetry can easily explain this measurement”, says Nierste.”*

Contents

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The $|V_{ub}|$ puzzle

Global analysis of $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing and $\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ mixing

GUT

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Conclusions

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

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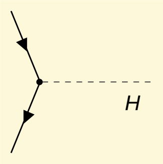

Yukawa lagrangian of quark fields:

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

The Yukawa matrices Y^f are arbitrary complex 3×3 matrices.

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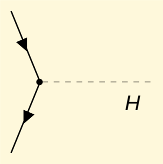

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The Yukawa matrices Y^f are arbitrary complex 3×3 matrices.

Switch to a basis with diagonal mass matrices $M^f = Y^f v$.

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.

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The last rotation

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

diagonalizes Y^d, but puts V into the W boson vertices:

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

Flavor 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: $V_{ts}^* y_b \equiv V_{32}^* y_b = -6\cdot 10^{-4}$.

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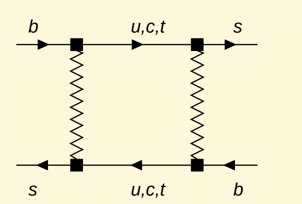
Flavor violation appears only in charged-current vertices. Flavor-changing neutral current (FCNC) processes are loop suppressed!

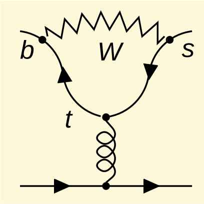
$\Rightarrow$ FCNC processes are sensitive to new physics.

Examples of FCNC processes:



$B_s - \overline{B}_s$ mixing

$|\Delta B| = 2$



penguin diagram

$|\Delta B| = 1$

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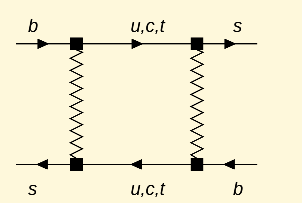

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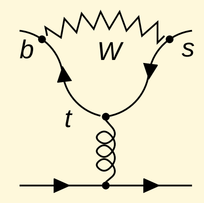

penguin diagram

$|\Delta B| = 1$

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

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

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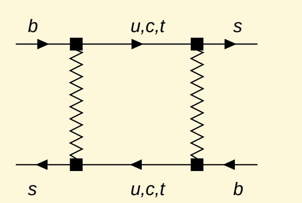

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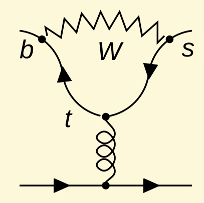

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$\Rightarrow$ Meson-antimeson mixing is more sensitive to generic NP than FCNC decay amplitudes, if $|\delta_{\rm FCNC}| > |V_{ts}|$.

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, $\overline{\rho}$, $\overline{\eta}$

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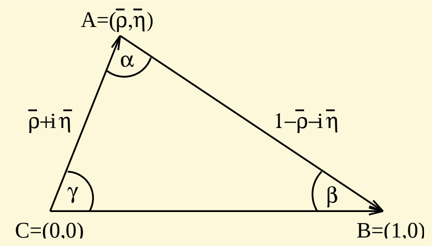
Unitarity triangle:

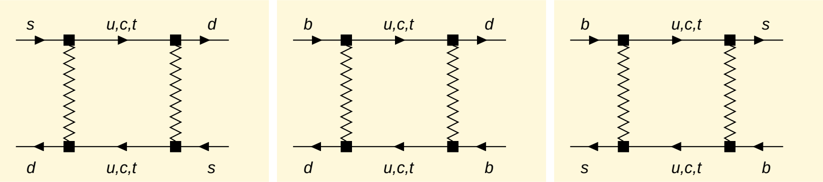
Exact definition:

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



New-physics analysers:

- Global fit to UT: overconstrain $(\bar{\rho}, \bar{\eta})$, probes FCNC processes $\mathrm{K}-\overline{\mathrm{K}}$, $\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ and $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing.



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- Global fit to $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing: mass difference Δm_s, width difference $\Delta\Gamma_s$, CP asymmetries in $B_s \to J/\psi\phi$ and $\overset{(-)}{B}_s \to X\ell\nu_\ell$.

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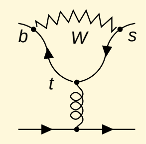
- Penguin decays: $B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$, $B \to K\pi$, $B_d \to \phi K_S$, $B_s \to \mu^+\mu^-$, $K \to \pi\nu\overline{\nu}$.



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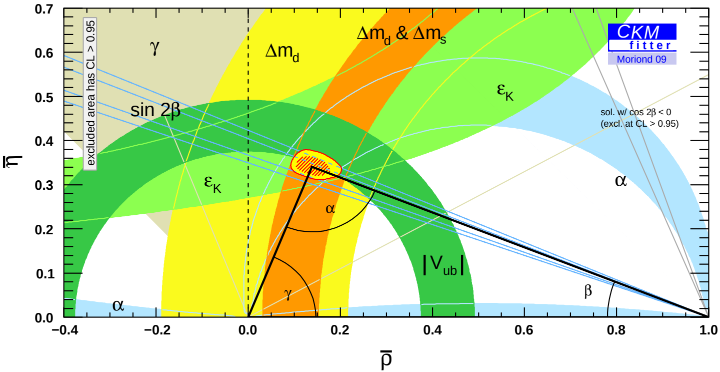
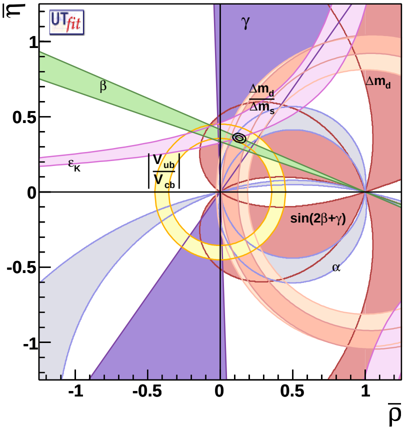
- CKM-suppressed or helicity-suppressed tree-level decays: $B^+ \to \tau^+\nu$, $B \to \pi\ell\nu$, $B \to D\tau\nu$, probe charged Higgses and right-handed W-couplings.

Global fit in the SM from CKMfitter:



Statistical method: Rfit, a Frequentist approach.

Global fit in the SM from UTfit:



Statistical method: Bayesian.

CKM matrix V

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

fixed by measurements of

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

$|V_{cb}| = (40.9 \pm 0.7) \cdot 10^{-3}$

and a global fit to $(\bar{\rho}, \bar{\eta})$

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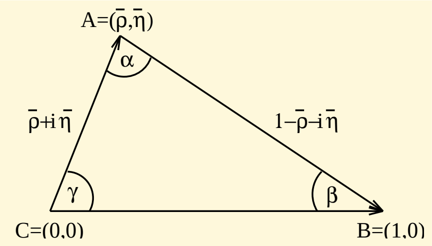

The $|V_{ub}|$ puzzle

Three ways to measure $|V_{ub}|$:

- exclusive decay $B \to \pi \ell \nu$,
- inclusive decay $B \to X \ell \nu$ and
- leptonic decay $B^+ \to \tau^+ \nu_\tau$.

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Average of several BaBar and Belle measurements:

$$B^{\rm exp}(B^+ \to \tau^+ \nu_\tau) \;=\; (1.68 \pm 0.31) \cdot 10^{-4}$$

Standard Model:

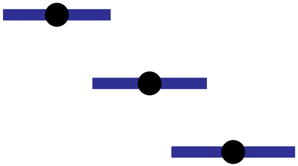
$$B(B^+ \to \tau^+ \nu_\tau) \;=\; 1.13 \cdot 10^{-4} \cdot \left(\frac{|V_{ub}|}{4 \cdot 10^{-3}} \right)^2 \left(\frac{f_B}{200\ \text{MeV}} \right)^2$$

The $|V_{ub}|$ puzzle

$$|V_{ub,\mathrm{excl}}| = (3.51 \pm 0.47) \cdot 10^{-3}$$

$$|V_{ub,\mathrm{incl}}| = (4.32 \pm 0.50) \cdot 10^{-3}$$

$$|V_{ub,B\to\tau\nu}| = (5.10 \pm 0.59) \cdot 10^{-3}$$



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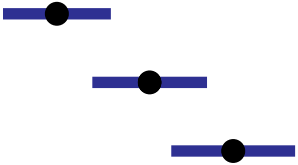

Here $f_B = (191 \pm 13)$ MeV is used:

$$\begin{aligned} |V_{ub,B\to\tau\nu}| &= \left[5.10 \pm 0.47|_{\mathrm{exp}} \pm 0.35|_{\mathrm{f_B}}\right] \cdot 10^{-3} \\ &= [5.10 \pm 0.59] \cdot 10^{-3} \end{aligned}$$

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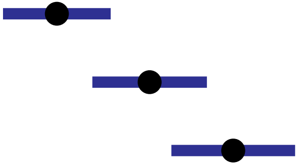

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&= [5.10 \pm 0.59] \cdot 10^{-3}
\end{aligned}
$$

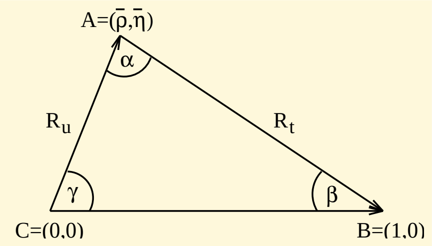
$\Rightarrow$ no puzzle with individual $|V_{ub}|$ determinations

The $|V_{ub}|$ puzzle

Indirect determination:

find $|V_{ub}| \propto |V_{cb}| R_u$

from $R_u = \dfrac{\sin\beta}{\sin\alpha}$



With $\alpha = 89^\circ{}^{+4.4^\circ}_{-4.2^\circ}$ and $\beta = 21.15^\circ \pm 0.89^\circ$ find

$$|V_{ub}|_{\text{ind}} = (3.41 \pm 0.15) \cdot 10^{-3}$$

Essential: β from $A_{\text{CP}}^{\text{mix}}(B_d \to J/\psi K_S)$

The $|V_{ub}|$ puzzle

$$|V_{ub,\mathrm{excl}}| = (3.51 \pm 0.47) \cdot 10^{-3}$$

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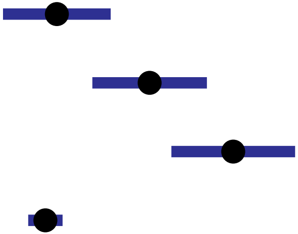

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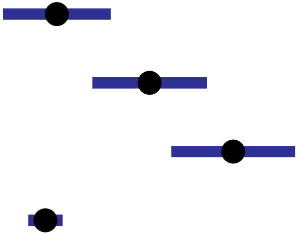


Alleviate the 2.9σ tension between $|V_{ub,\mathrm{ind}}|$ and $|V_{ub,B\to\tau\nu}|$ with new physics in

- $B^+ \to \tau^+\nu_\tau$
  E.g. right-handed W coupling, possible in SUSY through loop effects. Crivellin 2009

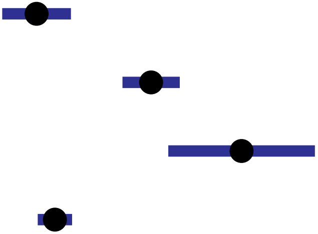
The $|V_{ub}|$ puzzle

$|V_{ub,\mathrm{excl}}| = (3.25 \pm 0.30) \cdot 10^{-3}$

$|V_{ub,\mathrm{incl}}| = (4.25 \pm 0.25) \cdot 10^{-3}$

$|V_{ub,B\to\tau\nu}| = (5.04 \pm 0.64) \cdot 10^{-3}$

$|V_{ub,\mathrm{ind}}| = (3.41 \pm 0.15) \cdot 10^{-3}$



Alleviate the 2.9σ tension between $|V_{ub,\mathrm{ind}}|$ and $|V_{ub,B\to\tau\nu}|$ with new physics in

- $B^+ \to \tau^+\nu_\tau$ or
- $A_{\mathrm{CP}}^{\mathrm{mix}}(B_d \to J/\psi K_S)$. $\leftarrow$ easier!

$\mathrm{B}-\overline{\mathrm{B}}$ 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.

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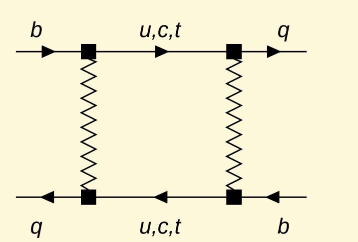
The mass matrix element M_{12}^q stems from the dispersive (real) part of the box diagram, internal t.

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



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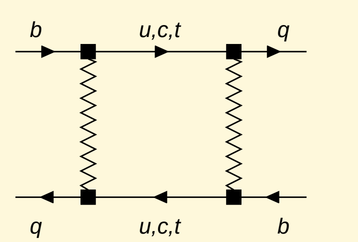

3 physical quantities in $\mathrm{B_q}-\overline{\mathrm{B}}_\mathrm{q}$ mixing:

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

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

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

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

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

May 14, 2010: DØ presents

$$a_{\rm fs} = (-9.57 \pm 2.51 \pm 1.46) \cdot 10^{-3}$$

for a mixture of B_d and B_s mesons with

$$a_{\rm fs} = (0.506 \pm 0.043) a_{\rm fs}^d + (0.494 \pm 0.043) a_{\rm fs}^s$$

The result is 3.2σ away from $a_{\rm fs}^{\rm SM} = (-0.20 \pm 0.03) \cdot 10^{-3}$.

A. Lenz, UN, 2006 and 2011

Averaging with an older CDF measurement yields

$$a_{\rm fs} = (-8.5 \pm 2.8) \cdot 10^{-3},$$

which is 2.9σ away from $a_{\rm fs}^{\rm SM}$.

DØ result presented 30 Jun 2011:

$$a_{\mathrm{fs}} = (-7.87 \pm 1.72 \pm 0.93) \cdot 10^{-3}$$

This differs from the SM value by 3.9σ!

Generic new physics

Phases $\phi_q = \arg(-M_{12}^q/\Gamma_{12}^q)$ in the Standard Model:

$$\phi_d^{\rm SM} = -4.3^\circ \pm 1.4^\circ, \qquad \phi_s^{\rm SM} = 0.2^\circ.$$

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 $\phi_s = \phi_s^{\rm SM} + \phi_s^\Delta \simeq \phi_s^\Delta$.

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

$$\Delta m_s = (17.77 \pm 0.10 \pm 0.07)\ \mathrm{ps}^{-1} \qquad \text{CDF}$$
$$\Delta m_s = (17.63 \pm 0.11 \pm 0.04)\ \mathrm{ps}^{-1} \qquad \text{LHCb (prelim)}$$

imply

$$|\Delta_s| = 1.03 \pm 0.14_{\rm (th)} \pm 0.01_{\rm (exp)}$$

Confront the DØ/CDF average

$$
\begin{aligned}
a_{\rm fs} &= (0.506 \pm 0.043) a_{\rm fs}^d + (0.494 \pm 0.043) a_{\rm fs}^s \\
&= (-8.5 \pm 2.8) \cdot 10^{-3}
\end{aligned}
$$

with (A. Lenz, UN, 2011)

$$
a_{\rm fs}^d = (5.4 \pm 1.0) \cdot 10^{-3} \cdot \frac{\sin \phi_d}{|\Delta_d|}, \qquad a_{\rm fs}^s = (5.1 \pm 1.0) \cdot 10^{-3} \cdot \frac{\sin \phi_s}{|\Delta_s|}.
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$\Rightarrow$ Need both $\phi_s < 0$ and $\phi_d < 0$.

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$\Rightarrow$ Need both $\phi_s < 0$ and $\phi_d < 0$.

$A_{\rm CP}^{\rm mix}(B_d \to J/\psi K_S) \propto \sin(2\beta + \phi_d^\Delta)$:

With $\phi_d^\Delta < 0$ find $\beta > \beta^{\rm SM} = 21^\circ$ $\Rightarrow$ $|V_{ub}|$ puzzle solvable.

Global analysis of $B_s-\overline{B}_s$ mixing and $B_d-\overline{B}_d$ mixing

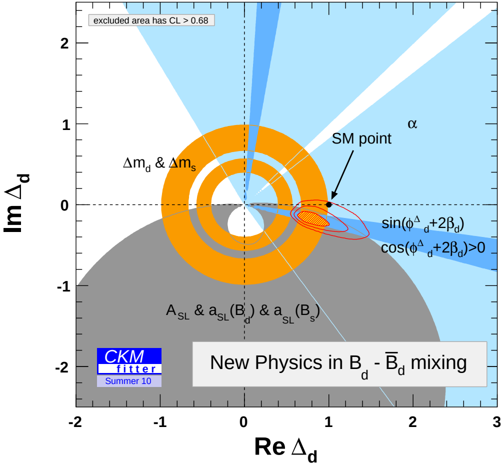
Based on work with A. Lenz and the CKMfitter Group
(J. Charles, S. Descotes-Genon, A. Jantsch, C. Kaufhold,
H. Lacker, S. Monteil, V. Niess) arXiv:1008.1593

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:

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

Result for $B_d - \overline{B}_d$ mixing:

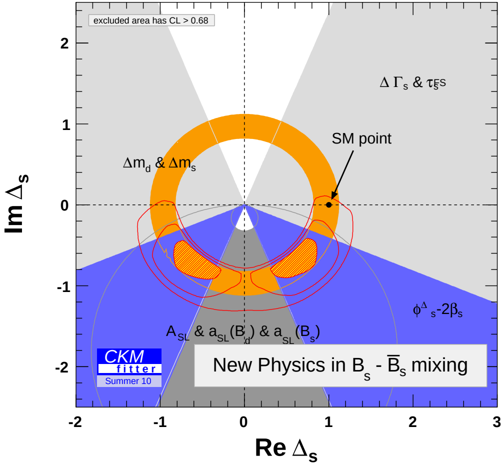


SM point $\Delta_d = 1$ disfavored by 2.7σ.

Main driver:

$B^+ \to \tau^+ \nu_\tau$

Result for $B_s - \overline{B}_s$ mixing:



SM point $\Delta_s = 1$ disfavored by 2.7σ.

without 2010 CDF/DØ and 2011 LHCb data on $B_s \to J/\psi\phi$

p-values:

Calculate $\chi^2/N_{\rm dof}$ with and without a hypothesis to find:

Hypothesis	p-value
$\Delta_d = 1$ (2D)	$2.7\ \sigma$
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Hypothesis	p-value
$\mathrm{Im}(\Delta_d) = 0$ (1D)	$2.7\ \sigma$
$\mathrm{Im}(\Delta_s) = 0$ (1D)	$3.1\ \sigma$
$\mathrm{Im}(\Delta_d) = \mathrm{Im}(\Delta_s) = 0$ (2D)	$3.8\ \sigma$

Fit result at 95%CL:

$$\phi_s^\Delta = (-52^{+32}_{-25})^\circ \qquad \text{(and } \phi_s^\Delta = (-130^{+28}_{-28})^\circ\text{)}$$

Compare with the 2010 CDF/DØ result from $B_s \to J/\psi\phi$:

CDF: $\phi_s^\Delta = (-27^{+44}_{-49})^\circ$ at 95%CL

DØ: $\phi_s^\Delta = (-42^{+59}_{-51})^\circ$ at 95%CL

Naive average: $\phi_s^{\text{avg}} = (-36 \pm 35)^\circ$ at 95%CL

DØ EPS 2011: $\phi_s^\Delta = (-30^{+22}_{-21})^\circ$ at 68%CL

LHCb Beauty 2011: $-199^\circ \leq \phi_s^\Delta \leq 13^\circ$ at 95%CL

Is the result driven by the DØ dimuon asymmetry?
One can remove $a_{\rm fs}$ as an input and instead predict it from the global fit:

$$a_{\rm fs} = \left(-4.2^{+2.9}_{-2.7}\right) \cdot 10^{-3} \qquad \text{at } 2\sigma.$$

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This is just 1.5σ away from the DØ/CDF average

$$a_{\rm fs} = (-8.5 \pm 2.8) \cdot 10^{-3}.$$

1.6σ discrepancy (Rfit method) with new DØ result

$$a_{\rm fs} = (-7.87 \pm 1.72 \pm 0.93) \cdot 10^{-3}$$

A fit to a real parameter $\Delta = \Delta_s = \Delta_d$ is not better than the SM fit and gives $\Delta = 0.90^{+0.31}_{-0.10}$ at 2σ.

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$\Rightarrow$ bad news for CMSSM and mSUGRA

Supersymmetry

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

No problem to get big effects in $B_s - \overline{B}_s$ mixing, but rather to suppress the big effects elsewhere.

Squark mass matrix

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

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

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E.g. Down-squark mass matrix:

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

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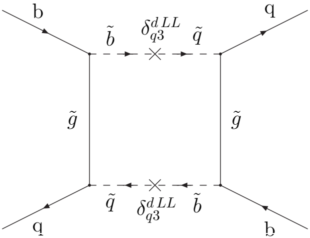
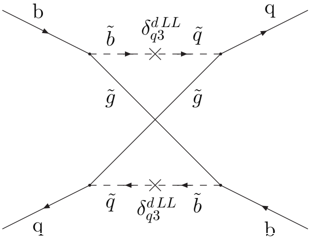
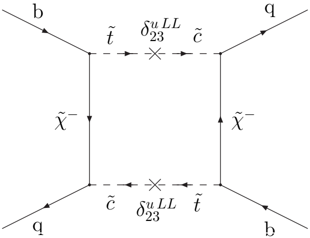
Not diagonal! $\Rightarrow$ new FCNC transitions.







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

Flavor and SUSY GUT

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

Consider SU(5) multiplets:

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

If the observed large atmospheric neutrino mixing angle stems from a rotation of $\mathbf{\overline{5}_2}$ and $\mathbf{\overline{5}_3}$, 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 $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing!

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

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

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

SO(10) superpotential:

$$
\begin{aligned}
W_Y \quad = \quad & \frac{1}{2}\, 16_i\, \mathrm{Y}_u^{ij}\, 16_j\, 10_H + \frac{1}{2}\, 16_i\, \mathrm{Y}_d^{ij}\, 16_j\, \frac{45_H\, 10'_H}{M_{\mathrm{Pl}}} \\
& + \frac{1}{2}\, 16_i\, \mathrm{Y}_N^{ij}\, 16_j\, \frac{\overline{16}_H \overline{16}_H}{M_{\mathrm{Pl}}}
\end{aligned}
$$

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 flavor violation"

The Yukawa matrices Y_u and Y_N are always symmetric. In the CMM model they are assumed to be simultaneously diagonalizable at the scale $M_{\rm Pl}$, 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

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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 effect in $B_s - \overline{B}_s$ mixing
tension with $M_h \geq 114\,\text{GeV}$

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 μ,
- tan β

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

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

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

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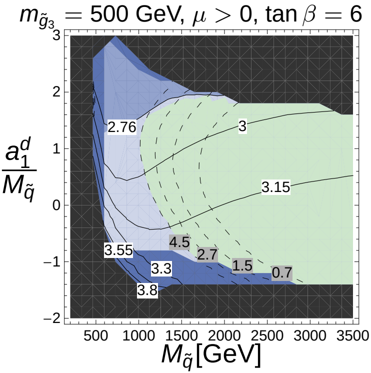
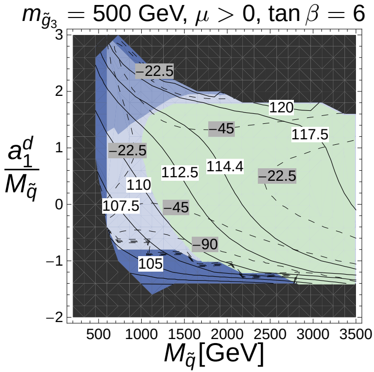
adjust CP phase ξ to approximate experimental Δ_s best.



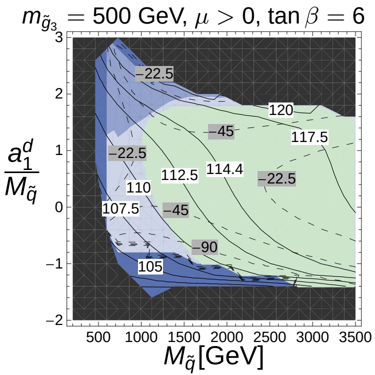
Black: negative soft masses[2]
Gray blue: excluded by $\tau \to \mu\gamma$
Medium blue: excluded by $b \to s\gamma$
Dark blue: excluded by $B_s - \overline{B}_s$ mixing
Green: allowed

solid lines: $10^4 \cdot Br(b \to s\gamma)$; dashed lines: $10^8 \cdot Br(\tau \to \mu\gamma)$.



gray labels: ϕ_s in degrees

white labels: M_h.



gray labels: ϕ_s in degrees

white labels: M_h.

It is easy to accomodate the large values of $|\phi_s|$ seen in the data.

For $\tan\beta = 3$ the bound $M_h \geq 114\,\text{GeV}$ is violated.

Radiative Flavor Violation

Origin of the SUSY flavor problem: Misalignment of squark mass matrices with Yukawa matrices.

Unorthodox solution: Set Y_{ij}^{u} and Y_{ij}^{d} to zero, except for $(i,j) = (3,3)$.

$\Rightarrow$ No flavor violation from $Y_{ij}^{u,d}$ and $V_{\mathrm{CKM}} = 1$.

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Radiative flavor violation: S. Weinberg 1972

flavor from soft SUSY terms:

W. Buchmüller, D. Wyler 1983,
F. Borzumati, G.R. Farrar,
N. Polonsky, S.D. Thomas 1998, 1999
J. Ferrandis, N. Haba 2004

Today:

Strong constraints from FCNCs probed at B factories.

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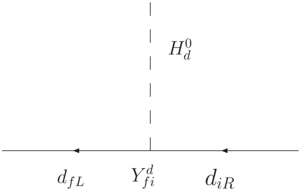
But: Radiative flavor violation in the MSSM is still viable, albeit only with A^d_{ij} and A^u_{ij} entering

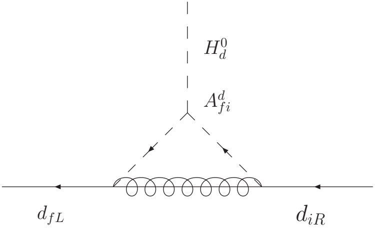
$$M^{\tilde{d}\,LR}_{ij} = A^d_{ij} v_d + \delta_{i3}\delta_{j3} y_b \mu v_u, \qquad M^{\tilde{u}\,LR}_{ij} = A^u_{ij} v_u + \delta_{i3}\delta_{j3} y_t \mu v_d.$$

Requires heavy sparticles, with squark masses around or above 1 TeV.

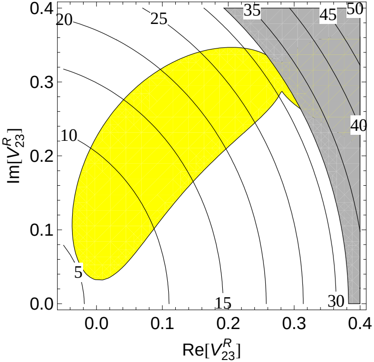
Andreas Crivellin, UN, PRD 79 (2009) 035018

Corrections to Yukawa couplings from A^d_{ij}:





If all flavor violation is generated from A^d_{ij}, there are correlated effects in $B(B_s \to \mu^+\mu^-)$ and $B_s - \overline{B}_s$ mixing:



Here $\tan\beta = 11$ and $M_{H^0} \simeq M_{A^0} = 400\,\mathrm{GeV}$. V^R_{23} parametrizes the $s_R \to b_L$ self-energy as $V^R_{23} \equiv \Sigma(s_R \to b_L)/m_b$.

Crivellin,Hofer,UN,Scherer, 1105.2818

Conclusions

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- A global fit to the UT indeed shows a slight preference for a new CP phase $\phi_d^\Delta < 0$, driven by $B(B^+ \to \tau^+\nu_\tau)$ (and possibly ϵ_K). In a simultaneously global fit to the UT and the $B_s - \overline{B}_s$ mixing complex a plausible picture of new CP-violating physics emerges.

Conclusions

- Large CP-violating contributions to $B_s - \overline{B}_s$ mixing are possible in supersymmetry without violating constraints from other FCNC processes. If confirmed the DØ/CDF results imply physics beyond the CMSSM and mSUGRA. We need "controlled" deviations from minimal flavor violation.

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- Models of GUT flavor physics with $\tilde{b}_R - \tilde{s}_R$ mixing driven by the atmospheric neutrino mixing angle can explain the Tevatron data on $\mathrm{B_s - \overline{B}_s}$ mixing without conflicting with $b \to s\gamma$ and $\tau \to \mu\gamma$.

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- The MSSM with radiative flavor violation permits sizable effects in $B(B_s \to \mu^+\mu^-)$ and $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing, but requires $\mathcal{O}(TeV)$ squark and gluino masses.

A pinch of new physics in $B-\overline{B}$ mixing?