Flavour physics, supersymmetry and GUTs

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FlaviA net

The Role of Heavy Fermions
in Fundamental Physics

Portorož 2011

May 14, 2010

Fermilab Wine&Cheese seminar, talk by Guennadi Borrisov:

Evidence for an anomalous like-sign dimuon charge asymmetry

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>
> *Joe Lykken, a theorist at Fermilab, said, “So I would not say that this announcement is the equivalent of seeing the face of God, but it might turn out to be the toe of God.”*

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

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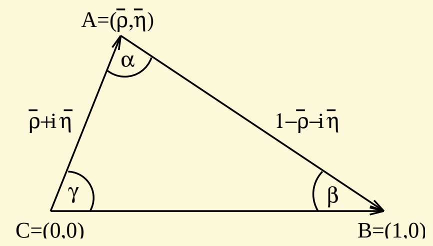
Unitarity triangle:

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



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:

$$\mathcal{B}^{\text{exp}}(B^+ \to \tau^+ \nu_\tau) = (1.64 \pm 0.34) \cdot 10^{-4}$$

B. Kowalewski, Beauty 2011

Standard Model:

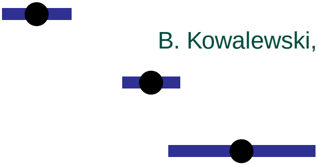
$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = 1.13 \cdot 10^{-4} \cdot \left(\frac{|V_{ub}|}{4 \cdot 10^{-3}} \right)^2 \left(\frac{f_B}{200 \text{ MeV}} \right)^2$$

The $|V_{ub}|$ puzzle

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

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

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



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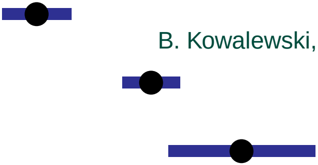

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Here $f_B = (191 \pm 13)$ MeV is used:

$$\begin{aligned} |V_{ub,B\to\tau\nu}| &= \left[5.04 \pm 0.53|_{\mathrm{exp}} \pm 0.35|_{\mathrm{f_B}}\right] \cdot 10^{-3} \\ &= [5.04 \pm 0.64] \cdot 10^{-3} \end{aligned}$$

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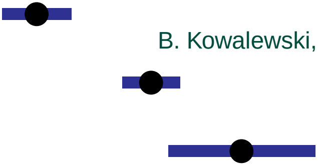

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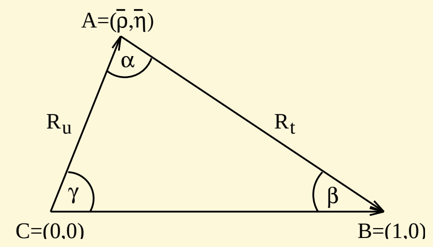
$\Rightarrow$ no puzzle with $B \to \tau\nu$ yet

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 $A^{\text{mix}}_{\text{CP}}(B_d \to J/\psi K_S)$

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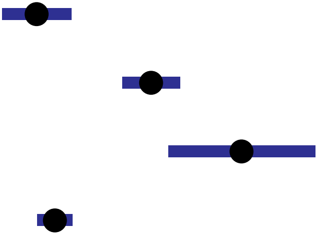

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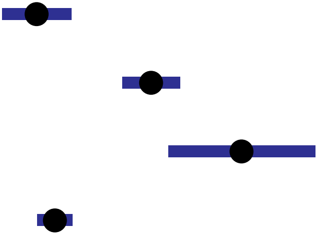

Alleviate the 2.9σ tension between $|V_{ub,\mathrm{ind}}|$ and $|V_{ub,B\to\tau\nu}|$ with new physics in

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

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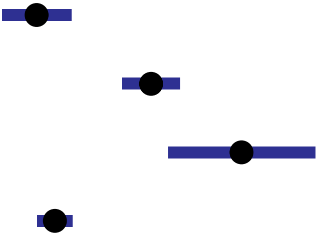

Alleviate the 2.9σ tension between $|V_{ub,\mathrm{ind}}|$ and $|V_{ub,B\to\tau\nu}|$ with new physics in

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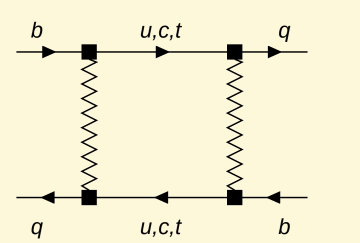

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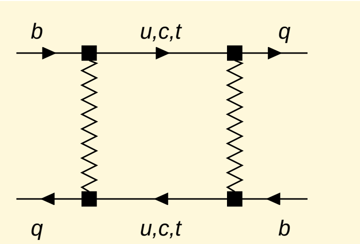

3 physical quantities in $\mathrm{B_q}-\overline{\mathrm{B}}_\mathrm{q}$ mixing:

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

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

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

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

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

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 $a_{\rm fs}^{\rm SM}$.

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

$$\Delta m_s = (17.77 \pm 0.10 \pm 0.07)\ \text{ps}^{-1} \qquad \text{CDF}$$

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

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

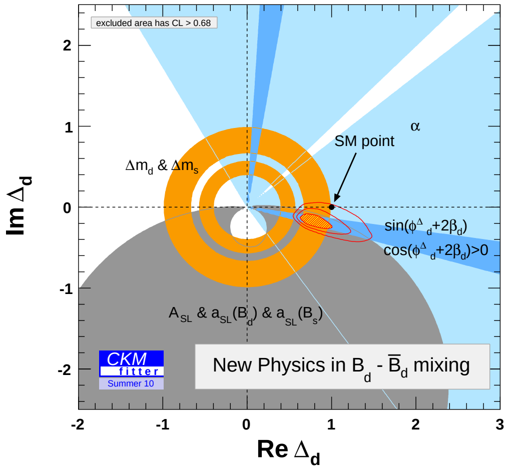
Rfit method: No statistical meaning is assigned to systematic errors and theoretical uncertainties.

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

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

$\Rightarrow$ see talk by A. Lenz, Tuesday 11:50 h

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



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

Main driver:
$B^+ \to \tau^+ \nu_\tau$

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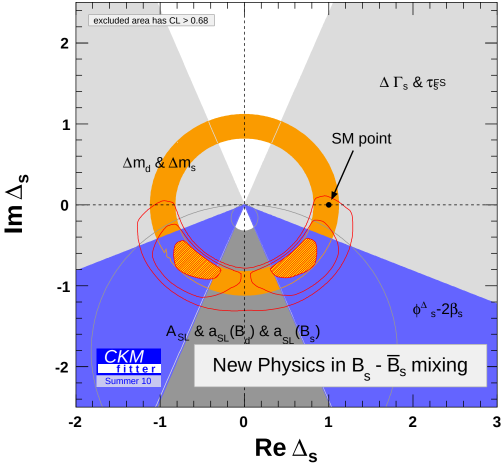

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without 2010 CDF/DØ data on $B_s \to J/\psi\phi$

p-values:

Calculate χ^2/N_{dof} with and without a hypothesis to find:

Hypothesis	p-value
$\Delta_d = 1$ (2D)	$2.7\ \sigma$
$\Delta_s = 1$ (2D)	$2.7\ \sigma$
$\Delta_d = \Delta_s$ (2D)	$2.1\ \sigma$
$\Delta_d = \Delta_s = 1$ (4D)	$3.6\ \sigma$

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$\Delta_d = \Delta_s$ (2D)	2.1 σ
$\Delta_d = \Delta_s = 1$ (4D)	3.6 σ

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

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: $\phi_s^\Delta = (-29^{+44}_{-49})^\circ$ at 95%CL

DØ: $\phi_s^\Delta = (-44^{+59}_{-51})^\circ$ at 95%CL

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

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

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

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

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

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

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 flavour 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.

Are there natural ways to motivate sizable new flavour violation in $B_s - \overline{B}_s$ mixing and $B_d - \overline{B}_d$ mixing while simultaneously suppressing flavour violation elsewhere?

Flavour and SUSY GUTs

Linking quarks to neutrinos: Flavour 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

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

and right-handed down squark mass matrix:

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

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 $B_s - \overline{B}_s$ mixing!

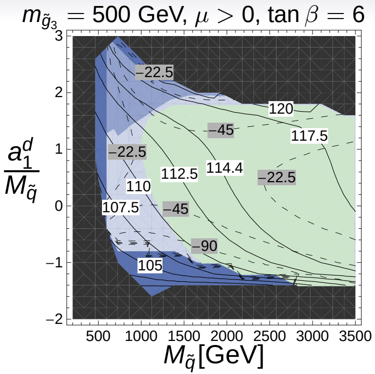
Chang-Masiero-Murayama model

The Chang–Masiero–Murayama (CMM) model is based on the symmetry breaking chain
$SO(10) \to SU(5) \to SU(3) \times SU(2)_L \times U(1)_Y$.

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
powerful constraint: $M_h \geq 114\,\text{GeV}$

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



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

$M_{\tilde{q}}$: squark mass of first two generations
a_1^d : trilinear term of first two generations

Dashed lines with gray labels: ϕ_s in degrees
Solid lines with white labels: M_h.

Conclusions

- The DØ result for the dimuon asymmetry in B_s decays supports the hints for $\phi_s < 0$ seen in $B_s \to J/\psi\phi$ data. The central value is easier to accomodate if both a_{fs}^s and a_{fs}^d receive negative contributions from new physics.

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- A global fit to the UT indeed shows a slight preference for a new CP phase $\phi^\Delta_d < 0$, driven by $B(B^+ \to \tau^+\nu_\tau)$ (and possibly ϵ_K). In a simultaneously global fit to the UT and the $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ 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.

Conclusions

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

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

Backup slides

Pull values

Quantity	Deviation wrt SM fit	wrt Sc. I	wrt Sc. II	wrt Sc. III
$\widehat{B}_K$	$0.0\ \sigma$	-	$0.0\ \sigma$	-
f_{B_s} [MeV]	$0.0\ \sigma$	$0.9\ \sigma$	$0.8\ \sigma$	$1.2\ \sigma$
$\widehat{\mathcal{B}}_{B_s}$	$1.2\ \sigma$	$0.8\ \sigma$	$0.9\ \sigma$	$0.3\ \sigma$
f_{B_s}/f_{B_d}	$0.0\ \sigma$	$0.9\ \sigma$	$0.0\ \sigma$	$0.0\ \sigma$
$\mathcal{B}_{B_s}/\mathcal{B}_{B_d}$	$1.0\ \sigma$	$0.9\ \sigma$	$1.0\ \sigma$	$0.9\ \sigma$
$\widetilde{\mathcal{B}}_{S,B_s}(m_b)$	$1.0\ \sigma$	$0.7\ \sigma$	$1.1\ \sigma$	$0.2\ \sigma$
α	$1.1\ \sigma$	$0.2\ \sigma$	$0.7\ \sigma$	$1.0\ \sigma$
$\phi_d^\Delta + 2\beta$	$2.8\ \sigma$	$0.8\ \sigma$	$2.6\ \sigma$	$1.3\ \sigma$
γ	$0.0\ \sigma$	$0.0\ \sigma$	$0.0\ \sigma$	$0.0\ \sigma$
$\phi_s^\Delta - 2\beta_s$	$2.3\ \sigma$	$0.5\ \sigma$	$2.4\ \sigma$	$1.6\ \sigma$

Quantity	Deviation wrt SM fit	wrt Sc. I	wrt Sc. II	wrt Sc. III
$\|\epsilon_K\|$	$0.0\ \sigma$	-	$0.0\ \sigma$	-
Δm_d	$1.0\ \sigma$	$0.9\ \sigma$	$1.0\ \sigma$	$0.8\ \sigma$
Δm_s	$0.3\ \sigma$	$0.7\ \sigma$	$0.9\ \sigma$	$1.2\ \sigma$
A_{SL}	$2.9\ \sigma$	$1.2\ \sigma$	$2.9\ \sigma$	$2.2\ \sigma$
a^d_{SL}	$0.9\ \sigma$	$0.2\ \sigma$	$0.8\ \sigma$	$0.3\ \sigma$
a^s_{SL}	$0.2\ \sigma$	$0.7\ \sigma$	$0.2\ \sigma$	$0.0\ \sigma$
$\Delta\Gamma_s$	$1.0\ \sigma$	$0.2\ \sigma$	$1.1\ \sigma$	$0.9\ \sigma$
$\mathcal{B}(B \to \tau\nu)$	$2.9\ \sigma$	$0.7\ \sigma$	$2.6\ \sigma$	$1.0\ \sigma$
$\mathcal{B}(B \to \tau\nu)$ and A_{SL}	$3.7\ \sigma$	$0.9\ \sigma$	$3.5\ \sigma$	$2.0\ \sigma$
$\phi_s^\Delta - 2\beta_s$ and A_{SL}	$3.3\ \sigma$	$0.8\ \sigma$	$3.3\ \sigma$	$2.3\ \sigma$
$\mathcal{B}(B \to \tau\nu)$, $\phi_s^\Delta - 2\beta_s$, A_{SL}	$4.0\ \sigma$	$0.6\ \sigma$	$3.8\ \sigma$	$2.1\ \sigma$

Dimension-5 terms

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.

SO(10) superpotential

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

with the Planck mass $M_{\rm Pl}$ 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.

Methodology of CMM analyis

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 $m_{\tilde{g}_3}$,
- $\arg \mu$,
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RG evolution from M_{ew} to M_{Pl}: find universal soft terms a_0, m_0, $m_{\tilde{g}}$ and D .

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

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

adjust CP phase ξ to approximate experimental Δ_s best.