Correlations in Minimal $U(2)^3$ models and an SO(10) SUSY GUT model facing new data

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Outline for the next 20 minutes

1. Introduction
2. Correlations of $\Delta F = 2$ observables:
   - CMFV vs. $MU(2)^3$ models and the role of $|V_{ub}|$
3. SO(10) SUSY GUT: CMM model
   - Flavour structure
   - Phenomenology
4. Summary

LHCb results

There were hopes to find clear signals of NP in $\boxed{S_{\psi\phi} \text{ and } \mathcal{B}(B_s \to \mu^+\mu^-)}$, but...

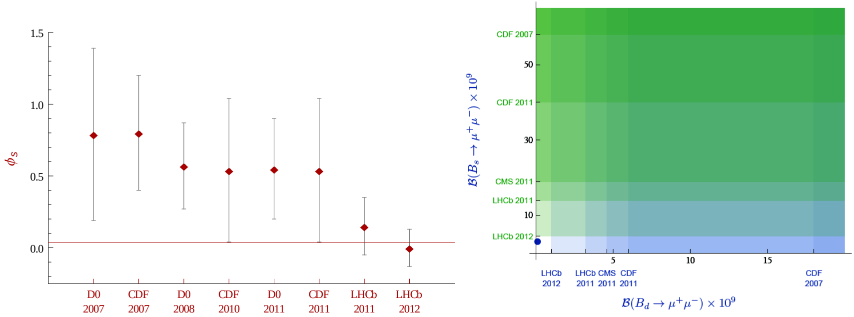
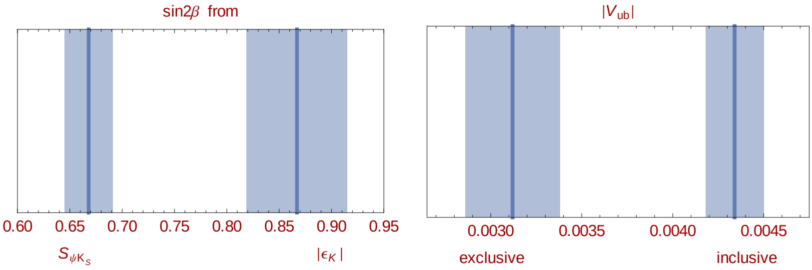


Figure: LHCb Collab: PRL 108 (2012), LHCb-CONF-2012-002, Phys. Lett. B 708 (2012), 1203.4493

Tensions in the Flavour data

$S_{\psi K_S} - |\varepsilon_K|$ tension $\longleftrightarrow$ $|V_{ub}|$ problem

- SM: $S_{\psi K_S} = \sin 2\beta$, $|\varepsilon_K| \propto \sin 2\beta |V_{cb}|^4$: 3.2$\sigma$ discrepancy
  [Buras, Guandagnoli, Phys. Rev. D 78 (2008), Lunghi, Soni, Phys. Lett. B 708 (2012)]
- $\beta_{\text{true}} = \beta_{\text{true}}(|V_{ub}|, \gamma)$



1. exclusive (small) $|V_{ub}|$: $S_{\psi K_S}$ in agreement with data, $|\varepsilon_K|$ below the data
2. inclusive (large) $|V_{ub}|$: $S_{\psi K_S}$ above data, $|\varepsilon_K|$ in agreement with data

Going beyond the SM

Great success of Cabibbo Kobayashi Maskawa picture

$\Rightarrow$ Strong constraints on flavour structure of NP models

Remainder of the talk:

1. Constraint Minimal Flavour Violation (CMFV):
   - CKM matrix is the only source of flavour and CP violation
   - only SM operators are relevant below electroweak scale
2. $U(2)^3$ models: third generation is special

   [Pomarol, Tommasini: hep-ph/9507462; Barbieri, Dvali, Hall: hep-ph/9512388; Barbieri, Buttazzo, Isidori, Jones-Perez, Lodone, Sala, Straub: 1105.2296, 1108.5125, 1203.4218, 1203.4218; Nierste, Crivellin, Hofer: 1111.0246, 0810.1613; Buras, JG: 1206.3878]

   Simplest non-MFV extension of the SM
3. SUSY-SO(10)-GUT: CMM model as an alternative to MFV

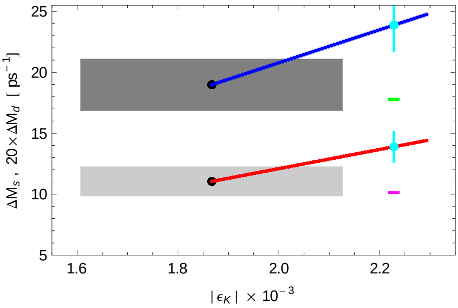
   [Chang, Masiero, Murayama: hep-ph/0205111; JG, Jäger, Knopf, Martens, Nierste, Scherrer, Wiesenfeldt: 1101.6047]

Phenomenological consequences of CMFV

- no new phases:

$$\varphi_K = \varphi_{B_d} = \varphi_{B_s} = 0 \quad \Rightarrow \quad S_{\psi K_S} = \sin 2\beta\,, \quad S_{\psi\phi} = \sin 2|\beta_s|$$

- $\Delta M_{s,d}$ and $|\varepsilon_K|$ can only be enhanced relative to SM (correlated)
- only exclusive $|V_{ub}|$: $S_{\psi K_S}$ as in SM and $|\varepsilon_K|$ can be enhanced, but problem with $\Delta M_{d,s}$ [Buras, JG: 1204.5064]



$U(2)^3$ model $\rightarrow$ 3rd generation is special

[see talk: F. Sala on Monday]

- Global flavour symmetry $G_F = U(2)_Q \times U(2)_u \times U(2)_d$ broken *minimally* by three spurions

$$\Delta Y_u = (\mathbf{2}, \overline{\mathbf{2}}, 1)\,, \quad \Delta Y_d = (\mathbf{2}, 1, \overline{\mathbf{2}})\,, \quad V = (\mathbf{2}, 1, 1)$$

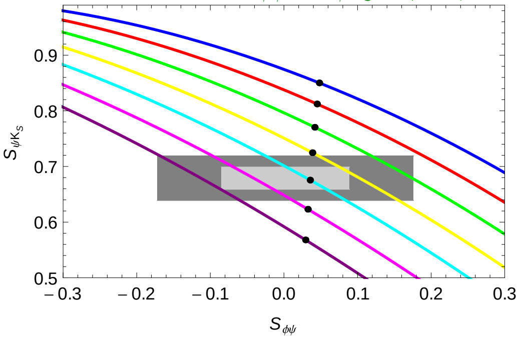
- motivated by observed pattern of quark masses and mixings
- natural embedding for SUSY with heavier 1st/2nd gen. and light 3rd gen. of squarks
- general consequences of $U(2)^3$ and breaking pattern concerning $\Delta F = 2$
    - K system governed by MFV structure (no new phases: $\varphi_K = 0$)
    - Corrections in $B_{d,s}$ system proportional to CKM structure of SM and universal: $(C_{B_d} = C_{B_s} =: r_B)$
    - new (universal) phase only in $B_{d,s}$ system $\varphi_d = \varphi_s = \varphi_{\text{new}}$
- These three condition + assumption: only SM operators relevant: $MU(2)^3$

Phenomenology in $MU(2)^3$

- $\Delta F = 2$ observables: [Buras, JG: 1206.3878]

$$S_{\psi K_S} = \sin(2\beta + 2\varphi_{\rm new})\,, \qquad S_{\psi\phi} = \sin(2|\beta_s| - 2\varphi_{\rm new})\,,$$
$$\Delta M_{s,d} = \Delta M_{s,d}^{\rm SM}\, r_B\,, \qquad \varepsilon_K = r_K \varepsilon_K^{\rm SM,tt} + \varepsilon_K^{\rm SM,cc+ct}$$

triple correlation $S_{\psi\phi} - S_{\psi K_S} - |V_{ub}|$



For different values of $|V_{ub}|$: 0.0046 (blue)– 0.0028 (purple)

negative $S_{\psi\phi}$ only for small $|V_{ub}|$ possible

incl. $|V_{ub}|$: $S_{\psi\phi} \geq S_{\psi\phi}^{\rm SM}$

Determine $|V_{ub}|$ in $MU(2)^3$ with $S_{\psi\phi}$ and $S_{\psi K_S}$

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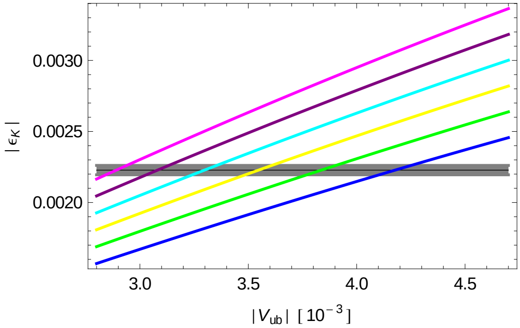

Connection between ε_K and $S_{\psi\phi}$ due to $|V_{ub}|$

$|V_{ub}| \in [0.0028, 0.0046]$
fixed $S_{\psi K_S} = 0.679$
r_K: 1 (blue)– 1.5 (magenta)

In concrete $U(2)^3$ models r_K and r_B can be correlated

Phenomenology in $MU(2)^3$

- $\Delta F = 2$ observables: [Buras, JG: 1206.3878]

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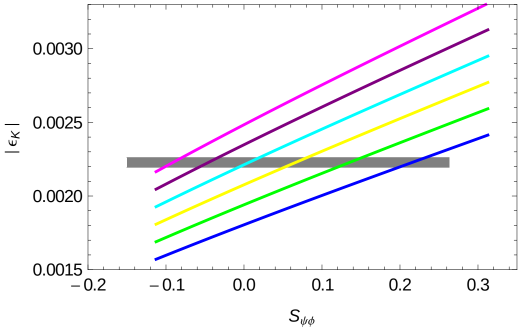

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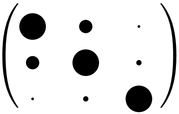
In concrete $U(2)^3$ models r_K and r_B can be correlated

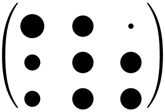
Concrete SUSY-SO(10)-GUT: CMM model

Flavour and SUSY GUTs

Flavour mixing:

- (left-handed) quarks: CKM matrix
- neutrinos: PMNS matrix

$V_{\mathrm{CKM}} =$ 

$U_{\mathrm{PMNS}} \approx$ 

SU(5) multiplets link quarks to leptons

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

Idea of Chang, Masiero, Murayama; Moroi

neutrino mixing angle $\theta_{23} \approx 45^\circ$ induce large $\tilde{b}_R - \tilde{s}_R$- and $\tilde{\tau}_L - \tilde{\mu}_L$-mixing
$\Rightarrow$ new $b_R \to s_R$ transitions from gluino-squark loops possible

Flavour structure CMM model

Key ingredients: weak basis with

$$\boxed{\mathrm{Y}_d = \mathrm{Y}_\ell^\top} = V_{\mathrm{CKM}}^\star \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix} U_D \,, \qquad U_D = U_{\mathrm{PMNS}}^* \,\mathrm{diag}(1,\, e^{i\xi},\, 1)$$

and right-handed down squark mass matrix:

$$m_{\tilde{d}}^2(M_Z) = \mathrm{diag}\left(m_{\tilde{d}_1}^2, m_{\tilde{d}_1}^2, m_{\tilde{d}_1}^2\,(1 - \Delta_{\tilde{d}})\right)$$

$\Delta_{\tilde{d}} \in [0,\, 1]$: relative mass splitting $\Rightarrow$

- As in $U(2)^3$ models: heavy 1st/2nd squark gen. but light 3rd gen.

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- As in $U(2)^3$ models: heavy 1st/2nd squark gen. but light 3rd gen.

Mass matrix for $\tilde{d}_R$, $\tilde{s}_R$, $\tilde{b}_R$:

$$m_{\tilde{D}}^2 = U_D\, m_{\tilde{d}}^2 U_D^\dagger \approx m_{\tilde{d}_1}^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & -\frac{1}{2}\Delta_{\tilde{d}} e^{i\xi} \\ 0 & -\frac{1}{2}\Delta_{\tilde{d}} e^{-i\xi} & 1 \end{pmatrix}$$

CP phase ξ affects CP violation only in B_s–$\bar{B}_s$ mixing! Different in $U(2)^3$ models

CMM model – short overview

More technical: SO(10) superpotential [Chang, Masiero, Murayama 03]

$$W_Y^{\mathrm{SO}(10)} = \frac{1}{2}\mathbf{16}_i\,\mathrm{Y}_1^{ij}\,\mathbf{16}_j\,\mathbf{10}_H + \mathbf{16}_i\,\mathrm{Y}_2^{ij}\,\mathbf{16}_j\,\frac{\mathbf{45}_H\,\mathbf{10}'_H}{2M_{\mathrm{Pl}}} + \mathbf{16}_i\,\mathrm{Y}_N^{ij}\,\mathbf{16}_j\,\frac{\overline{\mathbf{16}}_H\overline{\mathbf{16}}_H}{2M_{\mathrm{Pl}}}$$

$\mathrm{Y}_1^{ij} \to \mathrm{M}_u,\ \mathrm{M}_\nu^D,\qquad \mathrm{Y}_2^{ij} \to \mathrm{M}_d,\ \mathrm{M}_\ell,\qquad \mathrm{Y}_N^{ij} \to \mathrm{M}_{\nu_R}$

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$$Y_1^{ij} \to M_u,\, M_\nu^D, \qquad Y_2^{ij} \to M_d,\, M_\ell, \qquad Y_N^{ij} \to M_{\nu_R}$$

- Symmetry breaking via SU(5)

$$SO(10) \xrightarrow[\langle 45_H\rangle]{\langle 16_H\rangle, \langle\overline{16}_H\rangle} SU(5) \xrightarrow{\langle 45_H\rangle} G_{SM} \xrightarrow{\langle 10_H\rangle, \langle 10'_H\rangle} SU(3)_C \times U(1)_{em}$$

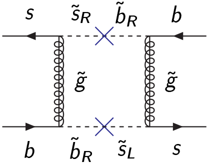
PMNS rotation is transferred to the (s)quark sector

Nonrenormalizable term $\propto Y_2$ term gives naturally small $\tan\beta$ and determines whole flavour structure

Flavour processes with typical CMM effects

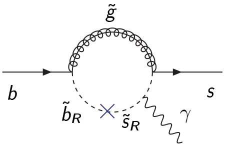
- neutrino mixing angle $\theta_{23} \approx 45^\circ$ connects 2nd and 3rd generation
- correlations between observables in quark- and lepton-sector

$B_s - \bar{B}_s$ mixing

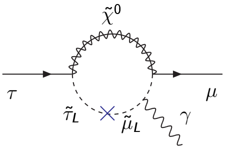


ΔM_s, ϕ_s

$b \to s\gamma$



$\tau \to \mu\gamma$



$$\mathcal{B}(\tau \to \mu\gamma) \leq 4.4 \cdot 10^{-8}$$

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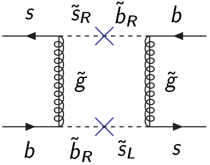

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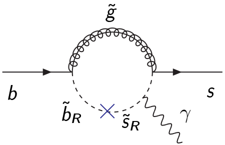

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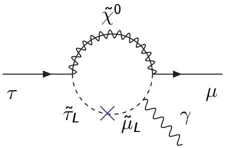


$\mathcal{B}(\tau \to \mu\gamma) \leq 4.4 \cdot 10^{-8}$

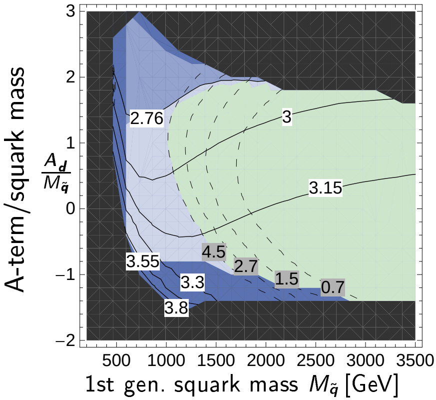
- What about $B_s \to \mu^+\mu^-$? $\Rightarrow$ CMM contributions are negligible ✓
- CMM effects in $K - \bar{K}$, ε_K, $B_d - \bar{B}_d$, $\mu \to e\gamma$ are suppressed, but small corrections due to dim-5-Yukawa terms needed to fix $\mathrm{Y}_d = \mathrm{Y}_\ell^\top$ for 1st/2nd gen.

[Trine,Wiesenfeldt,Westhoff: 0904.0378]

Phenomenology

Global analysis including RG evolution: Only 7 input paramters

$$M_{\text{ew}} \to M_{\text{GUT}} \to M_{SO(10)} \to M_{\text{Pl}} \to M_{SO(10)} \to M_{\text{GUT}} \to M_{\text{ew}}$$



■ : $m_{\tilde{f}}^2 < 0$, unstable vacuum

darkblue : excluded by $B_s - \overline{B}_s$

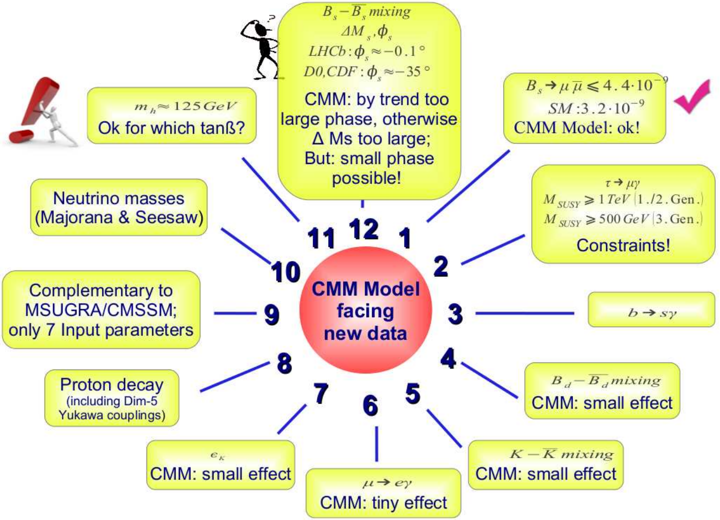
blue : excluded by $\mathcal{B}(b \to s\gamma)$: ——- $\boxed{3.15} \cdot 10^{-4}$

light blue : excluded by $\mathcal{B}(\tau \to \mu\gamma)$: - - - - - - 2.7 $\cdot 10^{-8}$

green : compatible with $B_s - \overline{B}_s$, $b \to s\gamma$, $\tau \to \mu\gamma$

- mass of the lightest Higgs $m_h \gtrsim 115$ GeV for $\tan\beta \geq 6$ → Update needed!

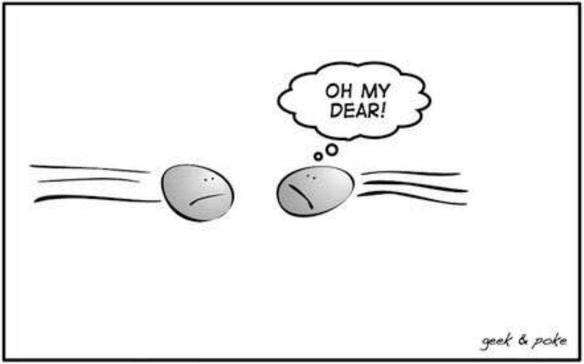
Summary of CMM model



Summary

- $|V_{ub}|$: situation unclear $\rightarrow$ need tree-level determination
- Triple correlation $S_{\psi\phi} - S_{\psi K_S} - |V_{ub}|$: crucial test of $MU(2)^3$ scenario (small dependence on γ)
- Further test on these $MU(2)^3$ models: ε_K and $\Delta M_{d,s}$
- Negative $S_{\psi\phi}$ is possible in $MU(2)^3$ in case of low (exclusive) $|V_{ub}|$ but then a 25% enhancement of ε_K is needed

Let's see what LHC will unveil about nature



LATELY INSIDE THE LHC:
2 PROTONS 0.000000000000000000001 SEC BEFORE THE COLLISION

Backup Slides

Phenomenology in $MU(2)^3$

- $\Delta F = 2$ observables: [Buras, JG: 1206.3878]

$$S_{\psi K_S} = \sin(2\beta + 2\varphi_{\text{new}}), \qquad S_{\psi\phi} = \sin(2|\beta_s| - 2\varphi_{\text{new}}),$$

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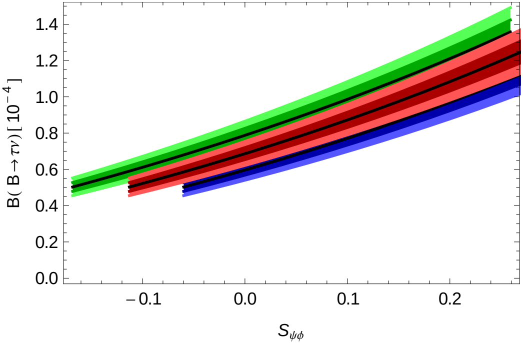


For fixed $S_{\psi K_S}$ (0.639 blue, 0.679 red, 0.719 green) correlation between $\mathcal{B}(B^+ \to \tau^+ \nu_\tau)$ and $S_{\psi\phi}$; $F_{B^+} = (190.6 \pm 9.2)$ MeV

New benchmark scenario

- 7 input parameters at $M_{SO(10)}$: $m_0^2 \quad m_{\tilde{g}} \quad D \quad a_0 \quad \arg\mu \quad \xi \quad (\tan\beta)$
- alternatively: inputs at M_{ew}: $m_{\tilde{u}_1} \quad m_{\tilde{d}_1} \quad m_{\tilde{g}} \quad a_1^d \quad \arg\mu \quad \xi \quad (\tan\beta)$

generic MSSM	mSUGRA/CMSSM	CMM model
$\approx$ 120 parameters	4 parameters & 1 sign	7 input parameters
SUSY flavour & CP problem	minimize flavour violation ad-hoc	clear flavour structure
no universality	universality at M_{GUT}	universality at M_{Pl} but broken at M_{GUT}
quarks & leptons unrelated		quark-lepton-interplay

Mass splittings

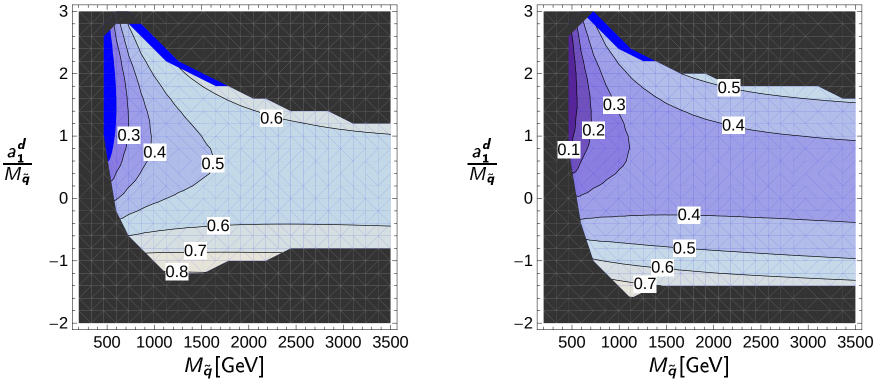
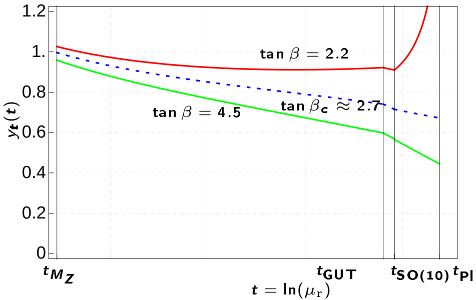


Figure: Relative mass splitting $\Delta_{\tilde d}^{\rm rel} = 1 - m^2_{\tilde d_3}/m^2_{\tilde d_2}$ among the bilinear soft terms for the right-handed squarks of the second and third generations with $\tan\beta = 3$ (left) and 6 (right) in the $M_{\tilde q}(M_Z) - a_1^d(M_Z)/M_{\tilde q}(M_Z)$ plane for sgn $\mu = +1$.

Perturbativity of y_t



- y_t has a quasi-fixed point $y_t^2/g^2 = 55/56 \simeq 1$ in SO(10) (for $\tan\beta_c \simeq 2.7$)
- $\tan\beta < 2.7 \Rightarrow y_t$ blow-up below M_{Pl}; $\tan\beta > 2.7 \Rightarrow y_t$ stays perturbative
- to test CMM: maximize flavour effects (large $\Delta_{\tilde{d}}$, i.e. large y_t, small $\tan\beta$)
- CMM model: $\boxed{2.7 \lesssim \tan\beta \lesssim 10}$

Higgs mass constraint

- For small $\tan\beta$ lower bound from LEP: $m_h \geq 114.4$ GeV
- MSSM: Higgs h^0 tends to be light at tree level: $m_h \leq M_Z|\cos(2\beta)|$
- corrections $\Delta m_h^2 \propto m_t^4 \ln\left(m_t^2/m_{\tilde{t}}^2\right) \Rightarrow$ (too) small for large y_t, because of RG evolution (small stop mass $m_{\tilde{t}}^2$)
- larger $\tan\beta$ reduces y_t and size of flavour effects
- could be relaxed by allowing the Higgs multiplets to have different Planck-scale masses from the sfermions (similarly to the non-universal Higgs model (NUHM))

small $\tan\beta$	$\Leftrightarrow$	large flavor effects	$\Leftrightarrow$	(too) light h^0
larger $\tan\beta$	$\Leftrightarrow$	smaller flavor effects	$\Leftrightarrow$	sufficiently heavy h^0

Example point

$M_{\tilde q}$=1500 GeV, $m_{\tilde g_3}$=500 GeV, $a_1^d(M_Z)/M_{\tilde q}$=1.5, arg μ=0, tan β=6 $M_{ew} \xrightarrow{\text{Upward evolution}} M_{Pl}$

a_0=1273 GeV, m_0=1430 GeV, $m_{\tilde g}$=184 GeV $M_{Pl} \xrightarrow{\text{SO(10) \& SU(5) RGE}} M_{GUT}$

$$\hat{A}_u(M_{GUT}) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 46 \end{pmatrix} \text{GeV}, \quad \hat{A}_d(M_{GUT}) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0.3 & -3.5 \end{pmatrix} \text{GeV},$$

$$\hat{A}_\nu(M_{GUT}) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -0.0013 & 0.0023 & 43.4 \end{pmatrix} \text{GeV},$$

non-universal at M_{GUT}

$m_{\tilde\Phi}(M_{GUT})$=diag(1426,1426,1074) GeV

$m_{\tilde\Psi}(M_{GUT})$=diag(1444,1444,1077) GeV

$m_{\tilde N}(M_{GUT})$=diag(1459,1459,1078) GeV

$m_{H_u}(M_{GUT})$=1126 GeV, $m_{H_d}(M_{GUT})$=1446 GeV

$m_{\tilde g}(M_{GUT})$=211 GeV

non-universal at M_{GUT}

$\xrightarrow{\text{MSSM RGE}}$

$m_{\tilde g_1}$=83 GeV $m_{\tilde g_2}$=165 GeV μ=629 GeV

$m_{\tilde\chi_i^0}$=(640, 632, 159, <u>81</u>) GeV $m^2_{H_d}$=(1432 GeV)^2

$m_{\tilde\chi_i^\pm}$=(640, 159) GeV $m^2_{H_u}$=−(575 GeV)^2

$M_{\tilde l_i}$=(1427, 1427, 1074, 1462, 1462, 1095) GeV

$M_{\tilde u_i}$=(1519, 1519, 934, 1501, 1501, 485) GeV

$M_{\tilde d_i}$=(1519, 1519, 908, 1498, 1498, 1164) GeV

RG evolution

- 2-loop RGE in MSSM, 1-loop RGE in SU(5) and SO(10)
- relate Planck-scale inputs to a set of low-energy inputs:
  - masses of RH up- and down-squarks of 1st gen. $m_{\tilde{u}_1}$, $m_{\tilde{d}_1}$
  - trilinear term a_1^d of 1st gen.
  - gluino mass $m_{\tilde{g}}$
  - $\arg\mu$ and $\tan\beta$
- RG evolution from M_{ew} to M_{Pl}: find universal soft terms a_0, m_0, $m_{\tilde{g}}$ and D
- RG evolution back to M_{ew}: calculate $|\mu|$ from electroweak symmetry breaking
- Repeat RG evolution: $M_{ew} \to M_{\mathrm{Pl}} \to M_{ew}$: find all particle masses and MSSM couplings
- adjust CP phase ξ to fit data (enters RGE via U_D) and calculate observables

Universality of SUSY breaking

Assumption of the model:
SUSY is broken flavour blind at $M_{\rm Pl}$ $\Rightarrow$ Universality of soft- und trilinear terms.
In this sense it is "minimal flavour violating".

$$\mathscr{L}_{\rm soft} = -\widetilde{16}_i\, m^{2\,ij}_{\widetilde{16}}\, \widetilde{16}_j - m^2_{\widetilde{10}_H}\, 10^*_H 10_H - m^2_{\widetilde{10}'_H}\, 10^*_{H'} 10_{H'}$$
$$- m^2_{\widetilde{\overline{16}}_H}\, \overline{16}^*_H \overline{16}_H - m^2_{\widetilde{16}_H}\, 16^*_H 16_H - m^2_{\widetilde{45}_H}\, 45^*_H 45_H$$
$$- \left(\frac{1}{2} \widetilde{16}_i\, A_1^{ij}\, \widetilde{16}_j\, 10_H + \frac{1}{2}\, \widetilde{16}_i\, A_2^{ij}\, \widetilde{16}_j\, \frac{45_H\, 10_{H'}}{M_{\rm Pl}} + \frac{1}{2}\, \widetilde{16}_i\, A_N^{ij}\, \widetilde{16}_j\, \frac{\overline{16}_H \overline{16}_H}{M_{\rm Pl}} + \text{h.c.} \right),$$
$$m^2_{\widetilde{16}_i} = m_0^2\ \mathbb{1}\,, \qquad m^2_{\widetilde{10}_H} = m^2_{\widetilde{10}_{H'}} = m^2_{\widetilde{45}_H} = m^2_{\widetilde{16}_H} = m^2_{\widetilde{\overline{16}}_H} = m_0^2\,,$$
$$A_1 = A_0\, Y_1\,, \qquad A_2 = A_0\, Y_2\,, \qquad A_N = A_0\, Y_N\,,$$

radiative corrections lead to a nonuniversal sfermion mass matrix at the GUT scale (diagonal in U-basis) [Hall, Kostelecky, Raby 86; Barbieri, Hall, Strumia95]

$$m^2_{\widetilde{16}_3} = m_0^2 - \Delta$$
$$m^2_{\widetilde{16}_1} \approx m^2_{\widetilde{16}_2} = m_0^2 + \delta$$

B_s–$\bar{B}_s$ mixing

$$M^s_{12,\,\mathrm{CMM}} = \frac{G_F^2 M_W^2 M_{B_s}}{12\pi^2} f_{B_s}^2 \hat{B}_{B_s} \left(V_{ts}^* V_{tb}\right)^2 \left(C_L(\mu_b) + C_R(\mu_b)\right)$$

$$C = C_L + e^{-2i\xi} \left| C_R^{\mathrm{CMM}} \right|$$

$$f_{B_s}\sqrt{\hat{B}_{B_s}} = (0.2580 \pm 0.0195)\ \mathrm{GeV}$$

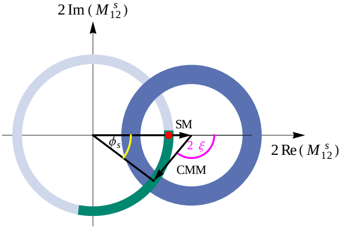


Figure: SM, exp. data, SM+CMM (Illustration not to scale).

Earlier Work

- Barbieri et al 1995:

  SO(10) model with small leptonic mixing
- Moroi JHEP **0003** (2000) 019; Phys. Lett. B **493** (2000) 366:

  SUSY SU(5) model with right-handed neutrinos, radiative effects due to atmospheric mixing angle
- Harnik et al 2011:

  analysis of effective model with large $\tilde{b} - \tilde{s}$ mixing, inspired by the CMM model
- Ciuchini et al 2004, 2007:

  SUSY breaking parametrised in mass insertion approximation, SU(5) GUT relations imposed at M_{GUT}