Flavour Physics in an SO(10) Grand Unified Model

Jennifer Girrbach

Technical University Munich (TUM)

in collaboration with S. Jäger, M. Knopf, W. Martens,
U. Nierste, C. Scherrer, S. Wiesenfeldt

JHEP **1106** (2011) 044 [arXiv:1101.6047]

EPS HEP 2011 Grenoble

20–27 July 2011

Outline for next 12 minutes

1. SUSY-GUTs
2. CMM model – a new benchmark scenario
   - Theory
   - Comparison with CMSSM/mSUGRA
   - Phenomenology
3. Conclusion

Why do we believe in SUSY-GUTs?

- SM quantum numbers? Charge quantization?
  Fermions nicely fit into SU(5) multiplets

$$\overline{\mathbf{5}} = (d_R^c,\, L), \quad \mathbf{10} \simeq (Q,\, u_R^c,\, e_R^c)$$

Why do we believe in SUSY-GUTs?

- SM quantum numbers? Charge quantization?
  Fermions nicely fit into SU(5) multiplets

$$\overline{\mathbf{5}} = (d_R^c,\, L), \quad \mathbf{10} \simeq (Q,\, u_R^c,\, e_R^c)$$

- SO(10): all SM fields per generation + ν_R fit in spinor rep.:

$$\mathbf{16} \to \mathbf{10} \oplus \overline{\mathbf{5}} \oplus \mathbf{1} = ((Q, u_R^c, e_R^c), (d_R^c, L), \nu_R^c)$$

Why do we believe in SUSY-GUTs?

- SM quantum numbers? Charge quantization?
  Fermions nicely fit into SU(5) multiplets

$$\overline{\mathbf{5}} = (d_R^c,\, L), \quad \mathbf{10} \simeq (Q,\, u_R^c,\, e_R^c)$$

- SO(10): all SM fields per generation + ν_R fit in spinor rep.:

$$\mathbf{16} \to \mathbf{10} \oplus \overline{\mathbf{5}} \oplus \mathbf{1} = ((Q, u_R^c, e_R^c), (d_R^c, L), \nu_R^c)$$

- GUTs need SUSY:
  - gauge coupling unification
  - hierarchy problem (heavy GUT particles destabilizes electroweak scale)
- But: SUSY flavour & CP problem

Flavour and SUSY GUTs

Flavour mixing:

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

$$V_{\text{CKM}} = \begin{pmatrix} \huge\bullet & \bullet & \cdot \\ \bullet & \huge\bullet & \cdot \\ \cdot & \cdot & \huge\bullet \end{pmatrix} \qquad U_{\text{PMNS}} \approx \begin{pmatrix} \Large\bullet & \Large\bullet & \\ \bullet & \Large\bullet & \Large\bullet \\ \bullet & \Large\bullet & \Large\bullet \end{pmatrix}$$

SU(5) multiplets link quarks to leptons

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

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

CMM Model

SO(10) gauge theory with superpotential [Chang, Masiero, Murayama 03]

$$W_Y^{SO(10)} = \frac{1}{2}\mathbf{16}_i\, Y_1^{ij}\, \mathbf{16}_j\, \mathbf{10}_H + \mathbf{16}_i\, Y_2^{ij}\, \mathbf{16}_j\, \frac{\mathbf{45}_H\, \mathbf{10}'_H}{2M_{Pl}} + \mathbf{16}_i\, Y_N^{ij}\, \mathbf{16}_j\, \frac{\overline{\mathbf{16}}_H \overline{\mathbf{16}}_H}{2M_{Pl}}$$

- $Y_1^{ij} \to M_u,\ M_\nu^D$, $Y_2^{ij} \to M_d,\ M_\ell$, $Y_N^{ij} \to M_{\nu_R}$
- Assumptions:
  - flavour symmetry (which is exact at M_{Pl}) is broken
  - Y_1 and Y_N simultaneously diagonalisable
  - breaking via SU(5)

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

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

Flavour structure CMM model

Key ingredients: weak basis with

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

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; generated by top-Yukawa RG effects

Flavour structure CMM model

Key ingredients: weak basis with

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

and right-handed down squark mass matrix:

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

$\Delta_{\tilde{d}} \in [0,\, 1]$: relative mass splitting; generated by top-Yukawa RG effects
Rotating Y_d to diagonal form (mass eigentstates)$\Rightarrow$ $\theta_{23} \approx 45^\circ$ enters $m^2_{\tilde{D}}$:

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

The CP phase ξ affects CP violation in B_s–$\bar{B}_s$ mixing!

New benchmark scenario?

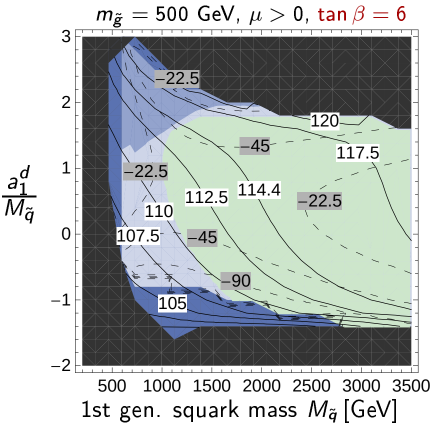
- 7 input parameters at $M_{SO(10)}$: $m_0^2 \quad m_{\tilde{g}} \quad D \quad a_0 \quad \arg\mu \quad \xi \quad (\tan\beta)$
- alternatively: inputs at M_{ew}: $m_{\tilde{u}_1} \quad m_{\tilde{d}_1} \quad m_{\tilde{g}} \quad a_1^d \quad \arg\mu \quad \xi \quad (\tan\beta)$
- RG evolution: $M_{ew} \to M_{Pl} \to M_{ew} \Rightarrow$ find all particle masses, MSSM couplings and calculate observables

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
Problem: suppress large effects elsewhere	cannot explain current flavour data (e.g. ϕ_s)	can fit ϕ_s and small effects in 1st/2nd gen.

Phenomenology

Global analysis of several observables:

$B_s - \overline{B}_s$ mixing, $b \to s\gamma$, $\tau \to \mu\gamma$, m_h (lightest Higgs mass)



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

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

medium blue : excluded by $b \to s\gamma$

light blue : excluded by $\tau \to \mu\gamma$

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

Higgs mass: ——- 114.4 GeV

ϕ_s in degrees: -------- -45°

Generic Results

- flavour effects $\propto$ mass splitting $\Delta_{\tilde{d}}$ (driven by RG effects of y_t)
- B_s–$\bar{B}_s$ mixing: free phase ξ can adjust ϕ_s
- powerfull constraint: $m_h \geq 114.4$ GeV $\Rightarrow$ excludes too small $\tan\beta$

Generic Results

- flavour effects $\propto$ mass splitting $\Delta_{\tilde{d}}$ (driven by RG effects of y_t)
- $B_s - \bar{B}_s$ mixing: free phase ξ can adjust ϕ_s
- powerfull constraint: $m_h \geq 114.4$ GeV $\Rightarrow$ excludes too small $\tan\beta$
- degenerate 1st/2nd gen. squark masses & nearly tribimaximal $U_{\mathrm{PMNS}} \Rightarrow$ effects suppressed in $K - \bar{K}$, ϵ_K, $\mu \to e\gamma$

Generic Results

- flavour effects $\propto$ mass splitting $\Delta_{\tilde{d}}$ (driven by RG effects of y_t)
- $B_s - \overline{B}_s$ mixing: free phase ξ can adjust ϕ_s
- powerfull constraint: $m_h \geq 114.4$ GeV $\Rightarrow$ excludes too small $\tan\beta$
- degenerate 1st/2nd gen. squark masses & nearly tribimaximal U_{PMNS} $\Rightarrow$ effects suppressed in $K - \overline{K}$, ϵ_K, $\mu \to e\gamma$
- realistic GUTs involve dim-5 Yukawa terms to fix $\mathsf{Y}_d = \mathsf{Y}_\ell^\top$ for 1st/2nd gen. $\Rightarrow$ not only $b_R \to s_R$ but also $b_R \to d_R$ and $d_R \to s_R$. Strongly constrained by $K - \overline{K}$ mixing [Trine, Wiesenfeldt, Westhoff 2009]
- Similar constraints can be found from $\mu \to e\gamma$

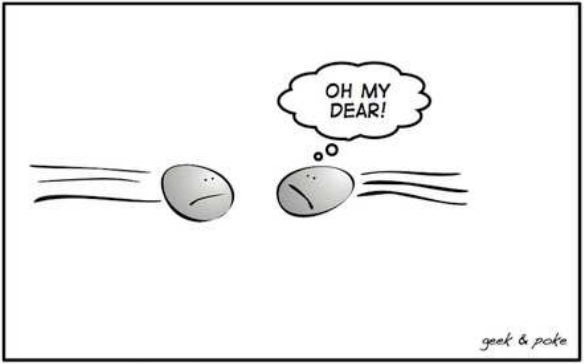
[Ko, Park, Yamaguchi 2008; Borzumati, Yamashita 2009];

[JG, Mertens, Nierste, Wiesenfeldt 2009].

Conclusions

- SUSY GUTs are theoretical well motivated scenarios with correlations between hadronic and leptonic observables
- If large CP violation in $B_s - \bar{B}_s$ mixing is confirmed $\Rightarrow$ physics beyond CMSSM and mSUGRA
- CMM model:
  - large atmospheric mixing angle $\theta_{23} \approx 45^\circ$ induces $b - s$- and $\tau - \mu$-transitions
  - free phase ξ can adjust CP violation in $B_s - \bar{B}_s$ mixing
  - only minor effects in $2 \to 1$ and $3 \to 1$ transitions
  - extensive RGE analysis to connect Planck-scale and low-energy parameters
  - Higgs potential still has to be worked out
  - new benchmark model?

Thanks for your attention



LATELY INSIDE THE LHC:
2 PROTONS 0.000000000000000001 SEC BEFORE THE COLLISION

Backup slides

Mass splittings

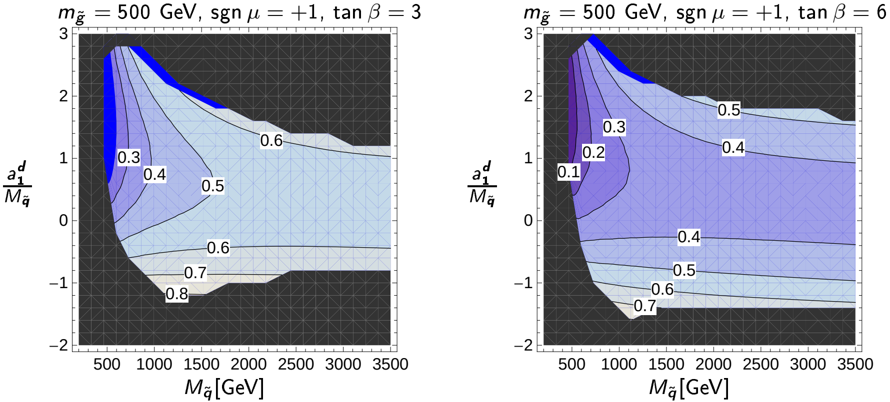


Figure: Relative mass splitting $\Delta_{\tilde{d}}^{\text{rel}} = 1 - m^2_{\tilde{d}_3}/m^2_{\tilde{d}_2}$ among the bilinear soft terms for the right-handed squarks of the second and third generations with $\tan\beta = 3$ (left) and 6 (right) in the $M_{\tilde{q}}(M_Z) - a_1^d(M_Z)/M_{\tilde{q}}(M_Z)$ plane for $m_{\tilde{g}} = 500$ GeV and sgn $\mu = +1$.

FCNC observables

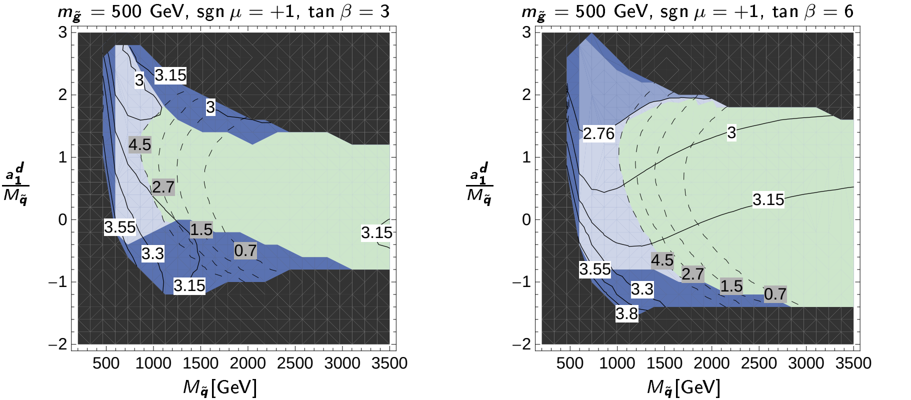
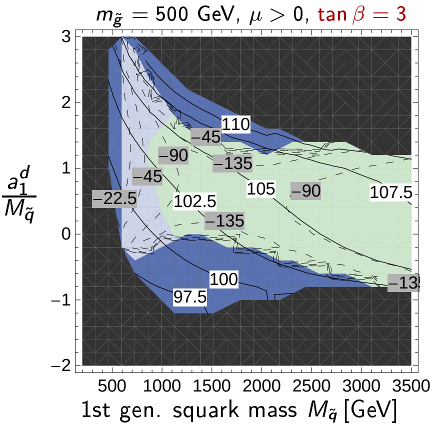


Figure: Correlation of FCNC processes with $\tan\beta = 3$ and $\tan\beta = 6$. $\mathcal{B}(b \to s\gamma)[10^{-4}]$ solid lines with white labels; $\mathcal{B}(\tau \to \mu\gamma)[10^{-8}]$ dashed lines with gray labels. Black region: $m^2_{\tilde{f}} < 0$ or unstable $|0\rangle$; dark blue region: excluded due to $B_s - \overline{B}_s$; medium blue region: consistent with $B_s - \overline{B}_s$ but excluded due to $b \to s\gamma$; light blue region: consistent with $B_s - \overline{B}_s$ and $b \to s\gamma$ but inconsistent with $\tau \to \mu\gamma$; green region: compatible with all three FCNC constraints.

Phenomenology

Global analysis of several observables:

$B_s - \overline{B}_s$ mixing, $b \to s\gamma$, $\tau \to \mu\gamma$, m_h (lightest Higgs mass)



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

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

medium blue: excluded by $b \to s\gamma$

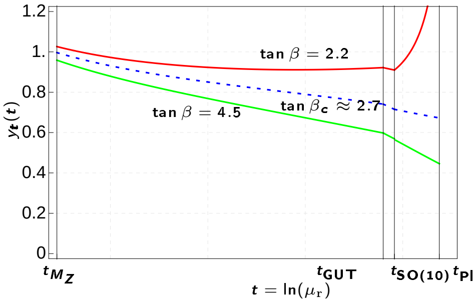
light blue: excluded by $\tau \to \mu\gamma$

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

Higgs mass: ——- 114.4 GeV

ϕ_s in degrees: -------- $-45°$

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“.

$$\begin{aligned}
\mathscr{L}_{\rm soft} = & -\widetilde{16}_i\, {\rm m}^{2\,ij}_{\widetilde{16}}\, \widetilde{16}_j - m^2_{\widetilde{10}_H}\, 10^*_H 10_H - m^2_{\widetilde{10}'_H}\, 10^*_{H'} 10_{H'} \\
& - m^2_{\widetilde{\overline{16}}_H}\, \overline{16}^*_H \overline{16}_H - m^2_{\widetilde{16}_H}\, 16^*_H 16_H - m^2_{\widetilde{45}_H}\, 45^*_H 45_H \\
& - \left(\frac{1}{2} \widetilde{16}_i\, {\rm A}_1^{ij}\, \widetilde{16}_j\, 10_H + \frac{1}{2}\, \widetilde{16}_i\, {\rm A}_2^{ij}\, \widetilde{16}_j\, \frac{45_H\, 10_{H'}}{M_{\rm Pl}} + \frac{1}{2}\, \widetilde{16}_i\, {\rm A}_N^{ij}\, \widetilde{16}_j\, \frac{\overline{16}_H \overline{16}_H}{M_{\rm Pl}} + {\rm h.c.} \right), \\
& {\rm m}^2_{\widetilde{16}_i} = m_0^2\ \mathbb{1}\,, \qquad m^2_{\widetilde{10}_H} = m^2_{\widetilde{10}_{H'}} = m^2_{\widetilde{45}_H} = m^2_{\widetilde{16}_H} = m^2_{\widetilde{\overline{16}}_H} = m_0^2\,, \\
& {\rm A}_1 = A_0\, {\rm Y}_1\,, \qquad {\rm A}_2 = A_0\, {\rm Y}_2\,, \qquad {\rm A}_N = A_0\, {\rm Y}_N\,,
\end{aligned}$$

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

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

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

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

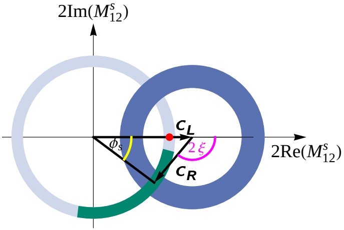


Figure: SM, exp. data, SM+CMM
(Illustration not to scale).

summer 2010:

$$-2\beta_s^{\mathrm{CDF}} \equiv -2\beta_s^{\mathrm{SM}} + \phi_s \in [-1.04, -0.04] \cup [-3.10, -2.16] \quad (68\%\ \mathrm{CL})$$

$$\phi_s^{\mathrm{D\O}} \equiv -2\beta_s^{\mathrm{SM}} + \phi_s = -0.76^{+0.38}_{-0.36}(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$

$$a_{\mathrm{fs}} = -0.0085 \pm 0.0028 \quad (68\%\ \mathrm{CL}).$$

Assuming no NP in a^d_{fs} and naively using a weighted average for $\sin\phi_s$:

$$\sin\phi_s = -0.77 \pm 0.47 \quad (95\%\ \mathrm{CL}).$$

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}