Flavour Physics in an SO(10) Grand Unified Model

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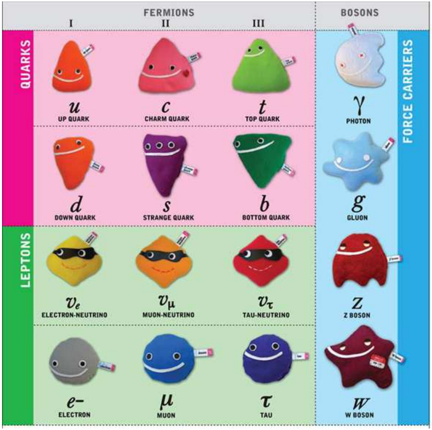
Outline for next 20 minutes

1. Why go beyond the SM?
2. SUSY SO(10) GUT model:
   CMM model – a new benchmark scenario
   [in collaboration with S. Jäger, M. Knopf, W. Martens, U. Nierste, C. Scherrer, S. Wiesenfeldt; JHEP **1106** (2011) 044 [arXiv:1101.6047]]
3. Summary

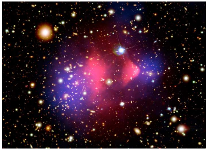
The Standard Model works very well!

$SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory



still missing particle: Higgs. . .

Why go beyond SM?



1. Experimental hints
   - Neutrino oscillations $\Rightarrow m_\nu \neq 0, \Delta L_i \neq 0$
   - Dark matter
   - matter-antimatter asymmetry
   - some anomalies in data ($(g-2)_\mu$, $S_{J/\psi\phi}$, $S_{J/\psi K_S} - \epsilon_K$, V_{ub}, A_b, $\Delta A_{CP}(D \to KK/\pi\pi)\ldots$)
2. Theoretical issues
   - Quantization of charge?
   - Unification of forces?
   - Stabilization of electroweak scale
   - Why three generations? Mixing structure?

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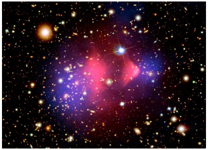

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Strategies for looking for NP:

- High energy: direct production of new particles $\Rightarrow$ Collider Physics
- High precision: quantum effects of new particle $\Rightarrow$ Flavour Physics

The matter with neutrinos

What is the SM with massive neutrinos?
We don't know!

- Including SM singlet ν_R? Dirac- or Majorana particles? Seesaw mechanism? Enlargement of scalar sector with Higgs triplet?

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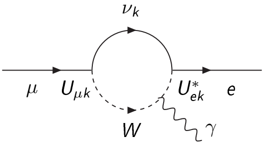
What about mixing of charged leptons in SM+$m_\nu \neq 0$?
In principle **yes**, via loops. But unobservable:

$$\mathcal{B}(\mu \to e\gamma) \approx \frac{3\alpha}{128\pi}\left(\frac{\Delta m_{21}^2}{M_W^2}\right)^2 \sin^2 2\theta_{12} \approx 10^{-54}$$



$\Rightarrow$ Detection of $\mu \to e\gamma$, $\tau \to e\gamma$, $\tau \to \mu\gamma$:
Clear signal of New Physics!

Why are atoms neutral?

The SM has a severe fine tuning problem... the hypercharge Y

Fermions	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
e_R	**1**	**1**	-1
$L = (\nu_L, e_L)^T$	**1**	**2**	$-\frac{1}{2}$
u_R	**3**	**1**	$\frac{2}{3}$
d_R	**3**	**1**	$-\frac{1}{3}$
$Q = (u_L, d_L)^T$	**3**	**2**	$\frac{1}{6}$

$$Q = T_3 + Y$$

The SM quantum numbers seems quite arbitrary

- **But:** $Q(\nu) = 0$, $Q(e) = 3Q(d)$ and $Q(u) = -2Q(d)$ to all digits behind the decimal point, so that neutrinos and atoms are electically neutral

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- The fermions nicely fits into SU(5) multiplets

$$\overline{\mathbf{5}} \to (\overline{\mathbf{3}}, \mathbf{1}, \tfrac{1}{3}) \oplus (\mathbf{1}, \mathbf{2}, -\tfrac{1}{2}) = (d_R^c,\ L)$$

$$\mathbf{10} \to (\overline{\mathbf{3}}, \mathbf{1}, -\tfrac{2}{3}) \oplus (\mathbf{3}, \mathbf{2}, \tfrac{1}{6}) \oplus (\mathbf{1}, \mathbf{1}, 1) \simeq (Q,\ u_R^c,\ e_R^c)$$

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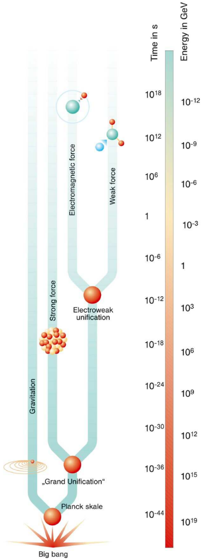
- SO(10): all SM fields per generation + ν_R fit in spinor rep.:

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

Consequences of Grand Unification

- unified force at high energy
- less parameters than SM (e.g. only one gauge coupling)



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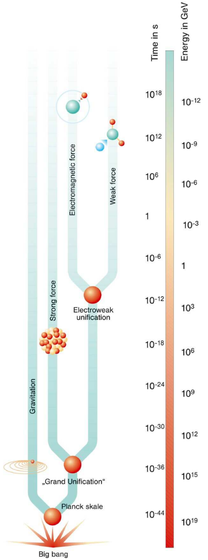
  - SU(5): Higgs coupling $\mathbf{10}_i Y_{ij} \mathbf{5}_j \overline{\mathbf{5}}_H \Rightarrow$ $\boxed{Y_d = Y_\ell^T}$
  - V_{CKM} can appear in Lepton sector
    U_{PMNS} can appear in Quark sector



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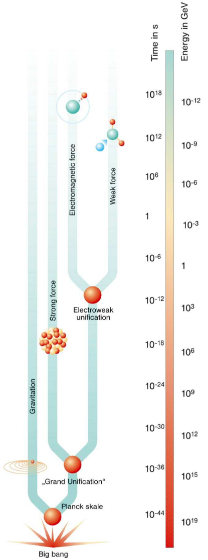
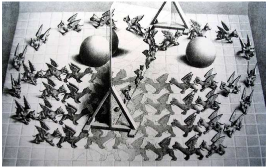
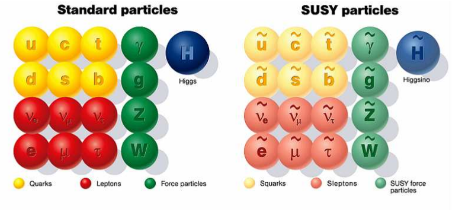
- Problems:
  - proton decay
  - "doublet-triplet-splitting" problem
  - hierarchy problem

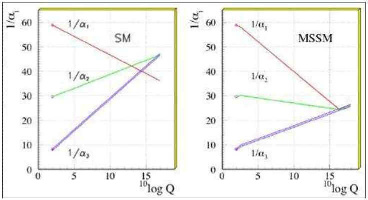


Grand Unified Theories "need" Supersymmetry

- gauge coupling unification
- hierarchy problem (heavy GUT particles destabilize electroweak scale)







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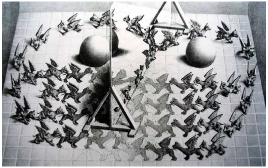
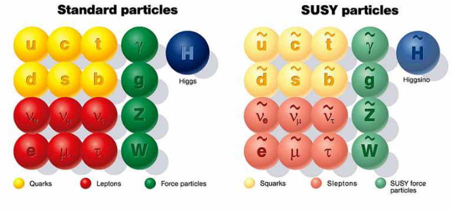
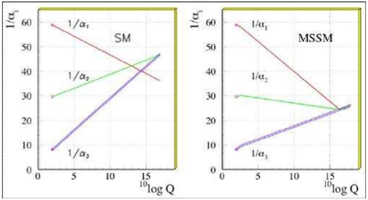




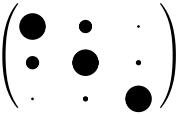


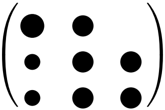
But: SUSY flavour & CP problem and no experimental hints so far. . .

Flavour and SUSY GUTs

Flavour mixing:

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

$V_{\text{CKM}} =$ 

$U_{\text{PMNS}} \approx$ 

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

CMM Model – short overview

- SUSY SO(10) gauge theory [Chang, Masiero, Murayama 03]
- Symmetry Breaking $SO(10) \to SU(5) \to G_{SM} \to SU(3)_C \times U(1)_{em}$
- Neutrino masses via seesaw

PMNS rotation is tranferred to the (s)quark sector

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More technical: Superpotential

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

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

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

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

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

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$\Delta_{\tilde{d}} \in [0,\, 1]$: relative mass splitting
Mass matrix for $\tilde{d}_R$, $\tilde{s}_R$, $\tilde{b}_R$:

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

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

New benchmark scenario

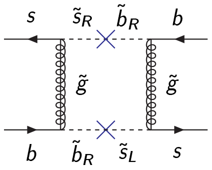
- 7 input parameters at $M_{SO(10)}$: $m_0^2 \quad m_{\tilde{g}} \quad D \quad a_0 \quad \arg\mu \quad \xi \quad (\tan\beta)$
- alternatively: inputs at M_{ew}: $m_{\tilde{u}_1} \quad m_{\tilde{d}_1} \quad m_{\tilde{g}} \quad a_1^d \quad \arg\mu \quad \xi \quad (\tan\beta)$

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

Flavour processes with typical CMM effects

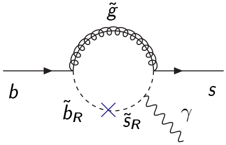
- neutrino mixing angle $\theta_{23} \approx 45^\circ$ connects 2nd and 3rd generation
- correlations between observables in quark- and lepton-sector

B_s–$\bar{B}_s$ mixing



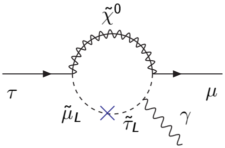
oscillation frequency ΔM_s
CP violation: ϕ_s (clean measurement $B_s \to J/\psi\phi$)

$b \to s\gamma$



Comparison between Exp. and SM leaves room for NP

$\tau \to \mu\gamma$



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

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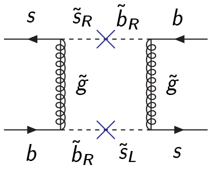

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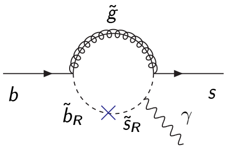

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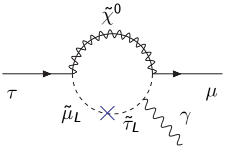

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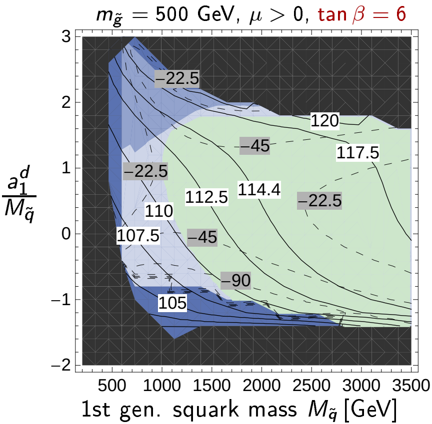
- What about $B_s \to \mu\bar{\mu}$?

Global analysis of several observables:

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



black: $m^2_{\tilde{f}} < 0$, 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

max. neg. ϕ_s in degrees: -------- −45°

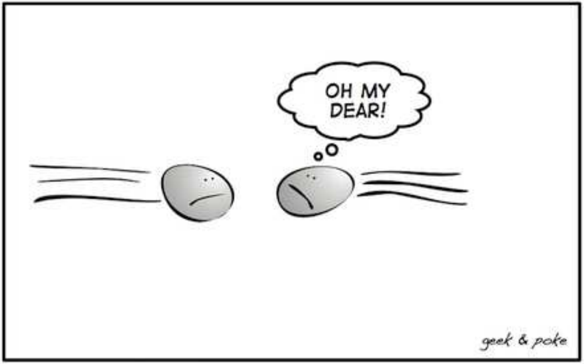
Further results

- $B_s - \bar{B}_s$ mixing: free phase ξ can induce large $\phi_s \neq 0$, e.g. $|S_{J/\psi\phi}| = 0 - 0.7$
- But $B_s \to \mu\bar{\mu}$ stays small (indepent of $S_{J/\psi\phi}$), because at low energies the CMM model is a special version of the MSSM with small $\tan\beta$: $\mathcal{B}(B_s \to \mu\bar{\mu})_{\text{CMM}} \lesssim 4 \cdot 10^{-9}$.
- degenerate 1st/2nd gen. squark masses & nearly tribimaximal $U_{\text{PMNS}} \Rightarrow$ effects suppressed in $K - \bar{K}$, 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 $K - \bar{K}$ mixing [Trine,Wiesenfeldt,Westhoff 2009]

Conclusions

- SUSY GUTs are theoretical well motivated scenarios with correlations between hadronic and leptonic observables
- 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
  - Global analysis: $B_s - \bar{B}_s$ mixing, ϕ_s, $b \to s\gamma$, $\tau \to \mu\gamma$, m_h, vacuum stability
  - new benchmark model; alternative to CMSSM

Thanks for your attention



LATELY INSIDE THE LHC:
2 PROTONS 0.0000000000000000000001 SEC BEFORE THE COLLISION

Backup slides

Mass splittings

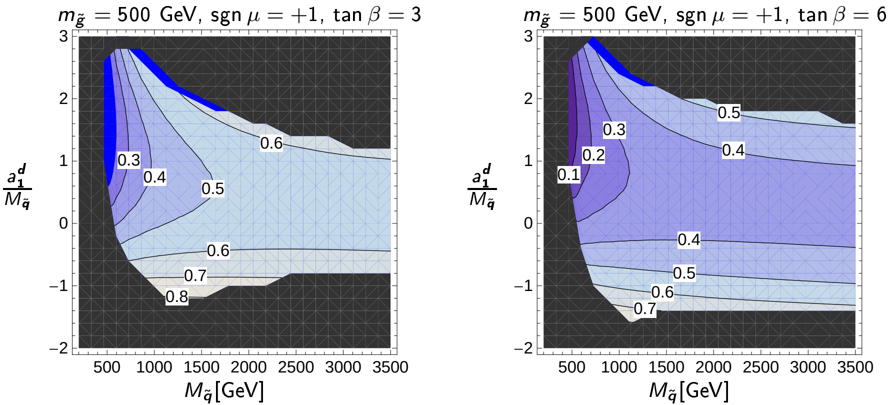


Figure: Relative mass splitting $\Delta^{\text{rel}}_{\tilde{d}} = 1 - m^2_{\tilde{d}_3}/m^2_{\tilde{d}_2}$ among the bilinear soft terms for the right-handed squarks of the second and third generations with tan $\beta = 3$ (left) and 6 (right) in the $M_{\tilde{q}}(M_Z) - a_1^d(M_Z)/M_{\tilde{q}}(M_Z)$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

FCNC observables

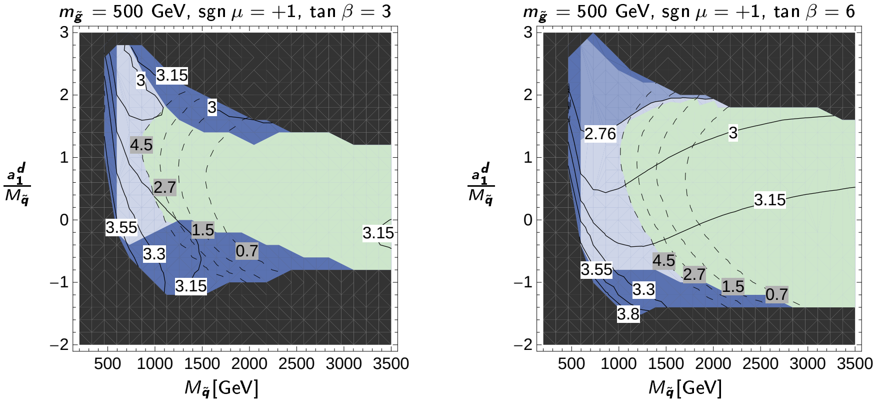
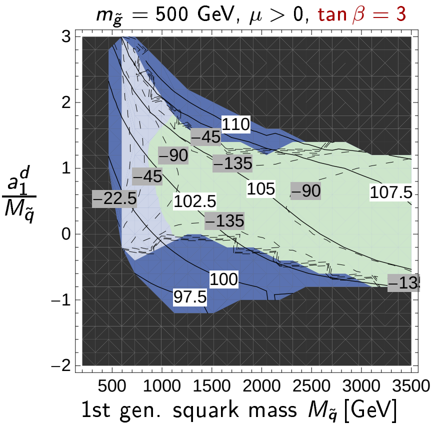


Figure: Correlation of FCNC processes with $\tan\beta = 3$ and $\tan\beta = 6$. $\mathcal{B}(b \to s\gamma)[10^{-4}]$ solid lines with white labels; $\mathcal{B}(\tau \to \mu\gamma)[10^{-8}]$ dashed lines with gray labels. Black region: $m_{\tilde{f}}^2 < 0$ or unstable $|0\rangle$; dark blue region: 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 $b \to s\gamma$

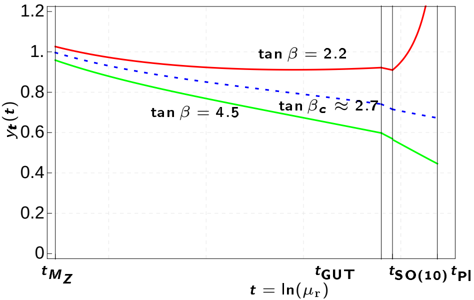
light blue: excluded by $\tau \to \mu\gamma$

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, $a_1^d(M_Z)/M_{\tilde{q}}=1.5$, $\arg\mu=0$, $\tan\beta=6$ $\quad M_{ew} \xrightarrow{\text{Upward evolution}} M_{Pl}$

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

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

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

non-universal at M_{GUT}

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

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

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

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

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

non-universal at M_{GUT}

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

$m_{\tilde{g}_1}=83$ GeV $\quad m_{\tilde{g}_2}=165$ GeV $\quad \mu=629$ GeV

$m_{\tilde{\chi}_i^0}=(640, 632, 159, \underline{81})$ GeV $\quad m_{H_d}^2=(1432\ \text{GeV})^2$

$m_{\tilde{\chi}_i^\pm}=(640, 159)$ GeV $\quad m_{H_u}^2=-(575\ \text{GeV})^2$

$M_{\tilde{l}_i}=(1427, 1427, 1074, 1462, 1462, 1095)$ 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".

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

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

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

B_s–$\bar{B}_s$ mixing

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

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

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

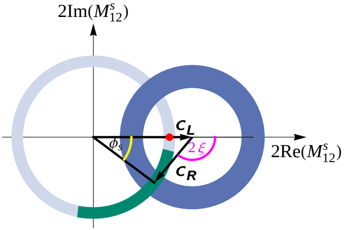


Figure: SM, exp. data, SM+CMM (Illustration not to scale).

summer 2010:

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

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

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

Assuming no NP in a_{fs}^d 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}