Flavour physics, supersymmetry, and GUTs

Ulrich Nierste

Karlsruhe Institute of Technology

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Supersymmetry

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

No problem to get a big effect in a given FCNC process, but rather to suppress big effects elsewhere (supersymmetric flavour problem).

With squark masses well beyond 1 TeV the supersymmetric flavour problem is substantially alleviated.

Squark mass matrix

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

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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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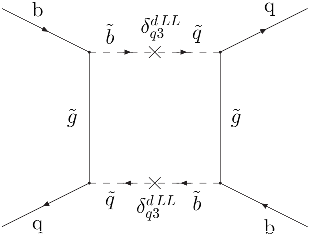
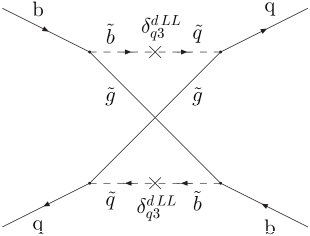
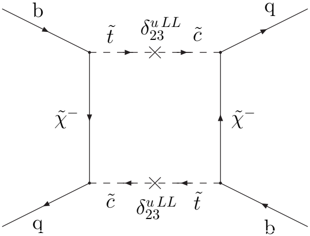
Not diagonal! $\Rightarrow$ new FCNC transitions.







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

Limiting cases:

Generic MSSM: too many free parameters

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Generic MSSM: too many free parameters

Minimal Flavour Violation (MFV): quark flavour transitions governed by CKM matrix, too small effects

Goal: Plausible scenarios with “controlled deviations” from MFV, permitting sizable new FCNC, even if squarks are heavy.

Flavour and SUSY GUT

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

Consider SU(5) multiplets:

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

If the observed large atmospheric neutrino mixing angle stems from a rotation of $\overline{\mathbf{5}}_2$ and $\overline{\mathbf{5}}_3$, 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

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

and right-handed down squark mass matrix:

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

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 CP violation in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing!

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Tri-bimaximal form of U_{PMNS} used here!

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SO(10) superpotential:

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

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 flavour violation"

The Yukawa matrices Y_u and Y_N are always symmetric. In the CMM model they are assumed to be simultaneously diagonalisable at the scale $M_{\rm Pl}$, where the soft SUSY-breaking terms are universal.

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But: FCNC transitions between quarks may involve $U_{\rm PMNS}$!

Chang-Masiero-Murayama model

2011 analysis:

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 effects in $B_s - \overline{B}_s$ mixing, $\tau \to \mu\gamma$

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

Phenomenological Motivation: In 2011 a global analysis of flavour data pointed to a large CP phase in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing, with the Standard Model disfavoured at $3.6\,\sigma$.

Lenz, UN, CKMfitter, 1008.1593

At the same time the reactor neutrino mixing angle θ_{13} was consistent with zero, so that the new quark FCNC transitions of the CMM model were confined to $b \to s$.

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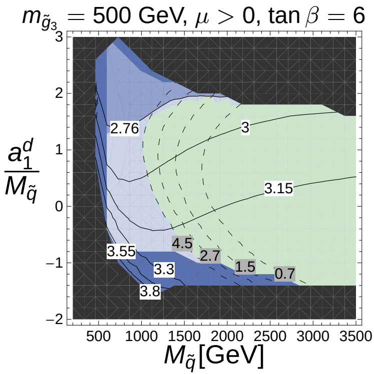
RG evolution from M_{ew} to M_{Pl}: find universal soft terms a_0, m_0, $m_{\tilde{g}}$ and D.

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

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

adjust CP phase ξ to approximate experimental Δ_s best.

2011 fit:



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: $10^8 \cdot Br(\tau \to \mu\gamma)$.

Two developments since 2011:

1. Measurement of a sizable θ_{13}:

$$\left[U^\dagger_{\mathrm{PMNS}}\, \mathrm{m}^2_{\tilde{d}}\, U_{\mathrm{PMNS}}\right]_{12} = \cos\theta_{13} \sin\theta_{13} \sin\theta_{23} \Delta_{\tilde{d}}$$

$\Rightarrow$ $B(\mu \to e\gamma) \leq 5.7 \cdot 10^{-13}$ (MEG 2013) pushes sfermion masses up.

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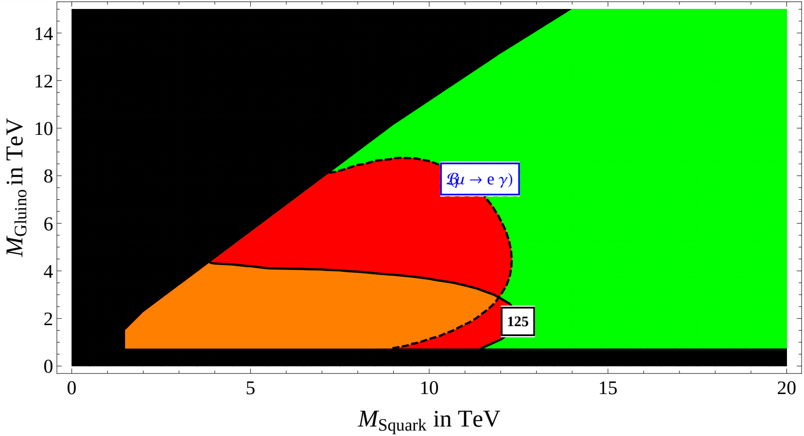
$\Rightarrow$ $B(\mu \to e\gamma) \leq 5.7 \cdot 10^{-13}$ (MEG 2013) pushes sfermion masses up.

2. Discovery of a Higgs particle with $M_h = 125$ GeV.
   Difficult to account for in CMM model.

J. Stöckel, UN, work in progress:



for $\tan\beta = 10$, $\mu > 0$, marginal dependence on a_1^d.
White label: Higgs mass. Red: excluded by $\mu \to e\gamma$ or $M_h = 125$ GeV.

All squark masses above 5 TeV, but lightest-neutralino mass can be 135 GeV!

Results

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Only constraints on gaugino masses from gaugino unification at M_{GUT} and experimental bounds on $m_{\tilde{g}_3}$. E.g. $m_{\tilde{\chi}_1^0} \simeq m_{\tilde{g}_1} = 135 GeV$ possible.

Conclusions

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Conclusions

- In view of the bounds on squark masses set by the LHC SUSY scenarios with “controlled deviations” from MFV are desirable.
- Models of GUT flavour physics with $\tilde{b} \to \tilde{s}$ transitions driven by the atmospheric neutrino mixing angle are substantially affected by $B(\mu \to e\gamma)$ and seriously challenged by $M_h = 125\,\text{GeV}$.
- The viable parameter space of the CMM model comes with squarks which are too heavy to be discovered. Gauginos can be light enough to be discovered, possibly also a stau.

The quantum numbers of the SM point towards a grand unified theory (GUT), the gauge couplings converge to a common GUT value at high energies, similarly y_τ and y_b converge, and neutrinos have small masses as predicted by GUT pioneers.

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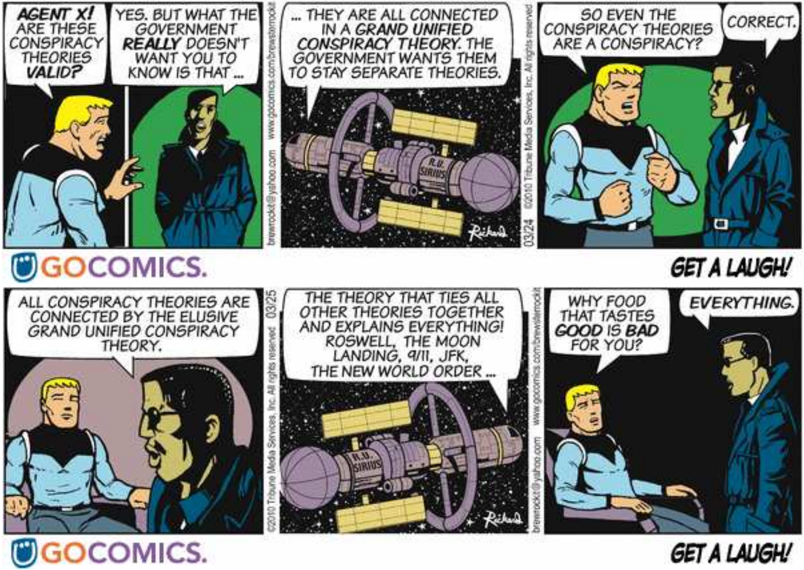
So is this just a conspiracy of Nature? Or even...


AGENT X! ARE THESE CONSPIRACY THEORIES VALID?
YES. BUT WHAT THE GOVERNMENT REALLY DOESN'T WANT YOU TO KNOW IS THAT ...
... THEY ARE ALL CONNECTED IN A GRAND UNIFIED CONSPIRACY THEORY. THE GOVERNMENT WANTS THEM TO STAY SEPARATE THEORIES.
SO EVEN THE CONSPIRACY THEORIES ARE A CONSPIRACY?
CORRECT.
GOCOMICS.
GET A LAUGH!
ALL CONSPIRACY THEORIES ARE CONNECTED BY THE ELUSIVE GRAND UNIFIED CONSPIRACY THEORY.
THE THEORY THAT TIES ALL OTHER THEORIES TOGETHER AND EXPLAINS EVERYTHING! ROSWELL, THE MOON LANDING, 9/11, JFK, THE NEW WORLD ORDER ...
WHY FOOD THAT TASTES GOOD IS BAD FOR YOU?
EVERYTHING.
GOCOMICS.
GET A LAUGH!