SUSY GUTs with Yukawa unification: the (major) role of FCNCs

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Based on:

Altmannshofer, DG, Raby, Straub

See also: Albrecht, Altmannshofer, Buras, DG, Straub

Introductory remarks

Exp. determined SM couplings
+
SM becomes supersymmetric above O(1 TeV)

Couplings numerically unify (w/ remarkable accuracy) at a high scale $M_G \approx O(10^{16}$ GeV)

☐ a (remarkable) coincidence

☑ first hint to a grand unified theory embedding the SM

This observed gauge coupling unification

✓ is very weakly dependent on the details of the SUSY spectrum assumed

✓ happens at just the "right" scale M_G:

- $M_G >$ scale where unacceptably large proton decay is generic
- $M_G <$ Planck scale, where the calculation wouldn't be trustworthy

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GUT groups

SO(10):

Simplest simple group where all (15) SM matter fields of generation *k* nicely fit into a single matter representation: $\mathbf{16}_k$

The 16th entry accommodates the right-handed neutrino: $(\nu_R)_k$

The appealing see-saw mechanism can be “built-in” automatically

The presence of SUSY guarantees stability of the ratios:

$$\frac{M_{\rm GUT}}{M_{\rm EW}}, \quad \frac{M_{\rm see-saw}}{M_{\rm EW}} \gg 1$$

Looking for further SUSY GUT tests

Generic predictions (besides coupling unification)

- **proton decay** [See *e.g.*: Dermisek, Mafi, Raby]
- **SUSY between the Fermi and the GUT scale,** hence, presumably, TeV-scale sparticles

However, in both cases detailed predictions require further model assumptions.

Are "robust" tests possible?

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needs specification of

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Hypothesis:

Yukawa coupling unification (across each matter multiplet)

- Generically also model-dependent (e.g. threshold corrections, role of higher-dim operators)
- However, for the 3rd generation: $Y_t \simeq Y_b \simeq Y_\tau \simeq Y_\nu$ it remains an appealing possibility

Note:

Yukawa interactions have dim 4.

It's not unlikely that they preserve info about the symmetries of the UV theory

3rd generation Yukawa unification (YU)

YU depends:

– on tanβ being large, O(50).

– on the details of the SUSY spectrum, since YU receives EW-scale threshold corrections, growing with growing tanβ

Hall, Rattazzi, Sarid

How to test this hypothesis within GUTs if these many unknowns can spoil it?

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Turn the argument around

Blazek, Dermisek, Raby

☑ Assume exact YU

☑ Impose the constraints from the *observed* top, bottom and tau masses

Learn about the implied GUT-scale parameter space

Assuming universal GUT-scale mass terms for sfermions (m_{16}, A_0) and for gauginos ($m_{1/2}$), one preferred region emerges:

$$A_0 \approx -2 m_{16}, \qquad \mu, m_{1/2} \ll m_{16}$$

These relations automatically lead to Inverted Scalar Mass Hierarchy

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Concrete example

Dermisek+Raby SO(10) SUSY GUT with a D_3 family symmetry

☑ Successfully describes EWPO, quark and lepton masses, CKM, PMNS.

Can one perform a deeper test of the model?

Since YU is sensitive to the whole SUSY spectrum,

to really test YU one needs additional observables, able to constrain the spectrum itself

Testing YU

Albrecht, Altmannshofer, Buras, D.G., Straub

Aim: *test YU beyond 3rd generation fermion masses*

Look at the observable consequences of the implied SUSY spectrum

Use info from FCNCs!

FCNCs: loop-suppressed observables highly sensitive to the details of the SUSY spectrum

Strategy: perform a global fit to the SO(10) GUT model parameters *including* FCNCs among the observables *directly in a fit*.

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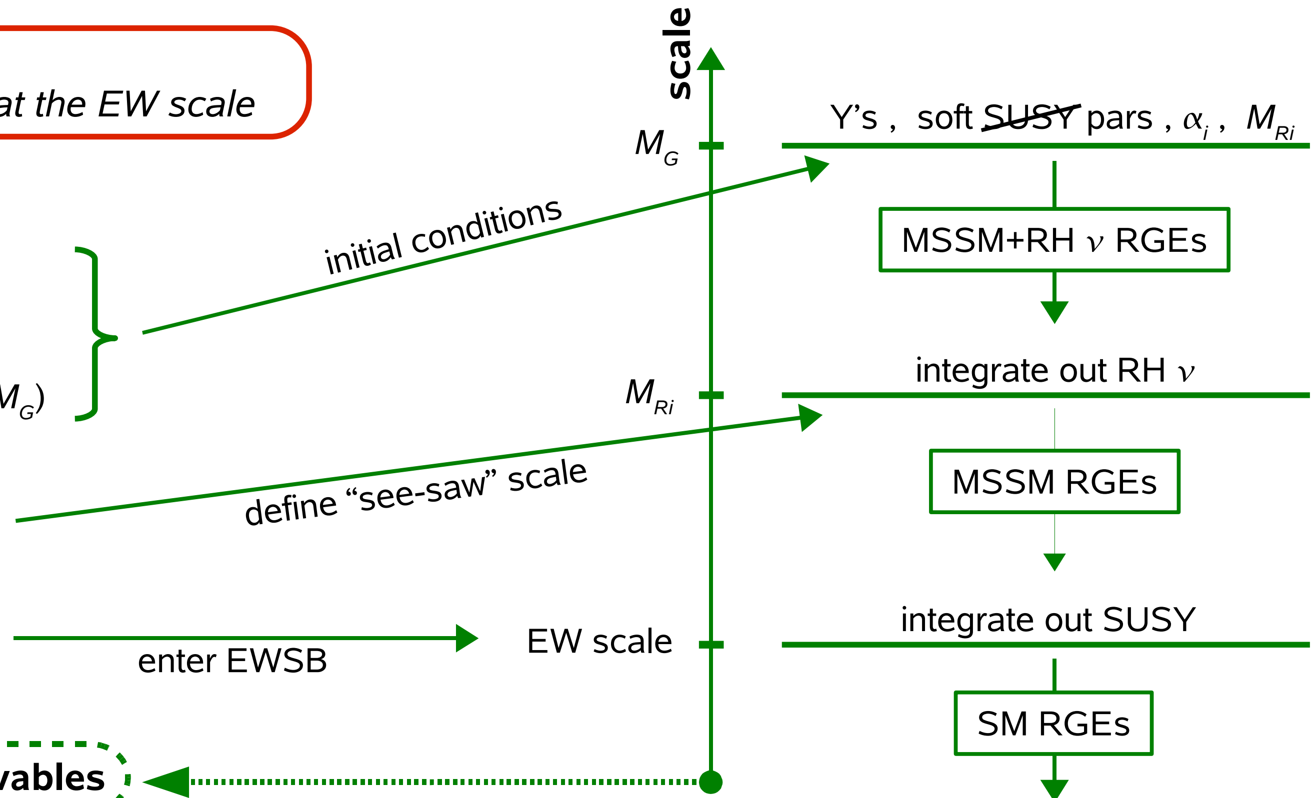
One step back:
how a GUT-scale model is tested at the EW scale

- unified coupling and scale: α_G , M_G
- soft SUSY-breaking params at M_G
- (textures entering the Yukawa's at M_G)
- right-handed neutrino masses M_{Ri}
- μ-term and tanβ at the EW scale



Compute observables

Short remarks on the procedure

☑ **All our conclusions** are assessed through a **fitting procedure** (manifestly parameterization invariant) i.e. by minimizing a χ^2 function defined as:

$$\chi^2[\text{model pars}] \equiv \sum_{i=1}^{N_{\text{obs}}} \frac{\left(f_i[\text{model pars}] - O_i\right)^2}{(\sigma_i^2)_{\text{exp}} + (\sigma_i^2)_{\text{theo}}}$$

f_i = model prediction for O_i

$$\{O_i\} = \begin{cases} \{M_W, M_Z, G_F, \alpha_{e.m.}, \alpha_s, M_t, m_b(m_b), M_\tau\} \\ \{\Delta M_s / \Delta M_d, B \to X_s \gamma, B \to X_s l^+ l^-, B \to \tau \nu\} \end{cases}$$

+ bounds on

- lightest Higgs,
- lightest part of SUSY spectrum,
- $B_s \to \mu^+ \mu^-$

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+ bounds on
  - lightest Higgs,
  - lightest part of SUSY spectrum,
  - $B_s \to \mu^+ \mu^-$

- ☑ Given the inverted scalar mass hierarchy, and being Yukawa also hierarchical, it is enough to parameterize the high-scale Yukawa's as

$$Y_{u,d} = \text{diag}\{0,\, 0,\, \lambda_{u,d}\}$$

Our conclusions are *independent* from the specific flavor model embedded in the SUSY GUT

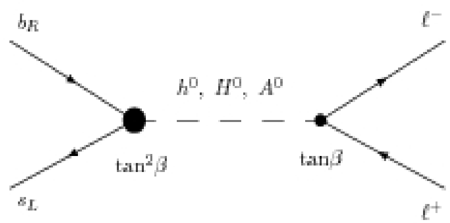
The two crucial FCNCs: $B_s \to \mu^+ \mu^-$ vs. $B \to X_s \gamma$

A generic expectation in YU is large tanβ

$\Rightarrow$ All the FCNCs need to be computed in the MSSM with large tanβ

☑ $\mathrm{BR}[B_s \to \mu^+ \mu^-]$

For large tanβ (and sizable A_t), dominated by double penguins with neutral Higgses



Enhancement going as:

$$\mathrm{BR}[B_s \to \mu^+ \mu^-] \propto A_t^2 \frac{\tan^6 \beta}{M_A^4}$$

Upper bound from CDF

$$\mathrm{BR}[B_s \to \mu^+ \mu^-]_{\exp} < 5.8 \times 10^{-8}$$

M_A > 500 GeV

Generic bound valid for all the heavy Higgs masses in our class of models

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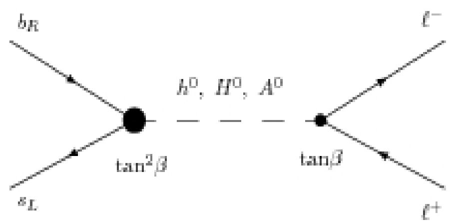

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☑ $\mathrm{BR}[B \to X_s \gamma]$

$$\mathrm{BR}[B \to X_s \gamma]^{\mathrm{exp}}_{E_\gamma > 1.6\mathrm{GeV}} = (3.55 \pm 0.26) \times 10^{-4}$$ { HFAG average }

$$\mathrm{BR}[B \to X_s \gamma]^{\mathrm{SM}}_{E_\gamma > 1.6\mathrm{GeV}} = (3.15 \pm 0.23) \times 10^{-4}$$ { Misiak *et al.*, PRL '07 }

The theory prediction for $B \to X_s \gamma$ must be "SM-like"

☑ $\mathrm{BR}[B \to X_s \gamma]$ [continued]

Very rough formula

$$\Gamma[B \to X_s \gamma] \approx \frac{G_F^2 \alpha_{\rm e.m.}}{32\pi^4} |V_{ts}^* V_{tb}|^2 m_b^5 \left(|C_7^{\rm eff}(\mu_b)|^2 + \ldots \right)$$

with $C_7^{\rm eff}(\mu_b) = C_{7,\rm SM}^{\rm eff}(\mu_b) + C_{7,\rm NP}(\mu_b)$

Dominant NP contributions are from charginos and Higgses. Gluinos play a minor role

$$C_{7,\rm NP}(\mu_b) \simeq C_7^{\tilde{\chi}^+}(\mu_b) + C_7^{H^+}(\mu_b)$$

Main features

- Higgs contrib's *add up* to the SM ones. However, Higgs contrib's are made small by the *lower bound on* M_A placed by $B_s \to \mu^+ \mu^-$

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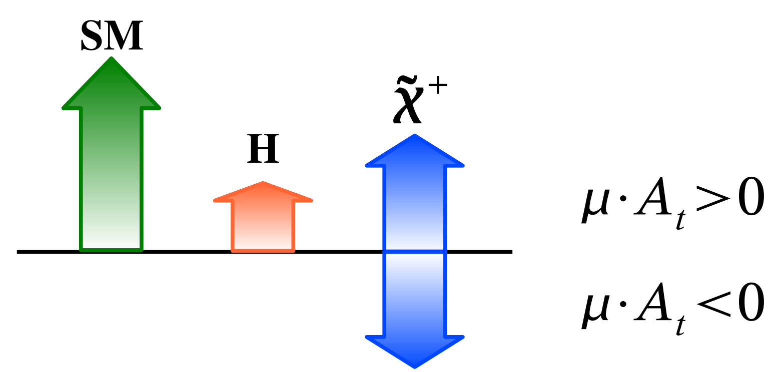
$$C_7^{\tilde{\chi}^+} \propto +\mu A_t \tan\beta \times \mathrm{sign}(C_7^{\mathrm{SM}})$$



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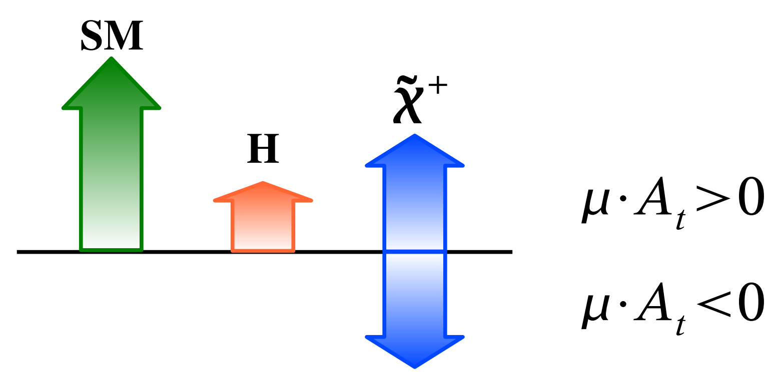
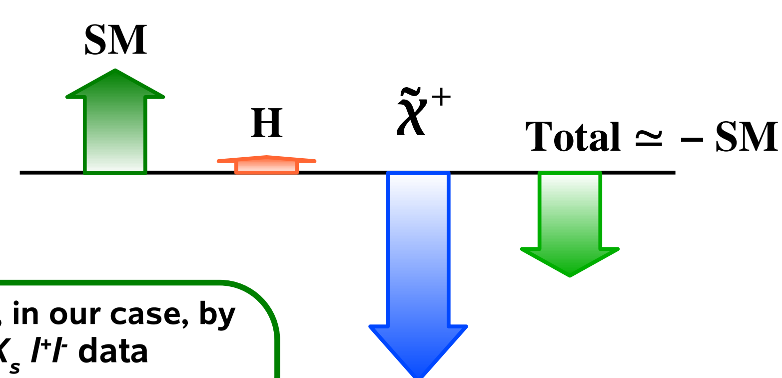


Specifically, chargino contrib's can be very large. As a matter of fact, for m_{16} < 4.5 TeV:

$\mu \cdot A_t < 0$ "prefers" the fine-tuned case:

$$C_{7,\rm NP}(\mu_b) \approx -2 C_{7,\rm SM}^{\rm eff}(\mu_b)$$



Challenged, in our case, by $B \to X_s l^+ l^-$ **data**
(see Gambino-Haisch-Misiak)

Summarizing the FCNC problem

- $B \to X_s \gamma$ would need a cancellation between Higgs and chargino contributions, however Higgses are suppressed because of the $B_s \to \mu^+ \mu^-$ bound

  The combined information from FCNCs (in particular $B \to X_s \gamma$ and $B_s \to \mu^+ \mu^-$) favors <u>lower values of tanβ</u> (or else, pushing m_{16} to decoupling values)

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Two questions arise

☑ Is the above tension among FCNCs for tanβ O(50) a *general* feature of SUSY GUTs with YU and universal GUT-scale soft terms ?

☑ Is this tension relieved if tanβ is below 50 (not too much in order not to spoil m_b) ?

Lowering tanβ: Complete YU $\xrightarrow{\text{relaxed to}}$ $Y_t \simeq Y_\nu$ and $Y_b \simeq Y_\tau$

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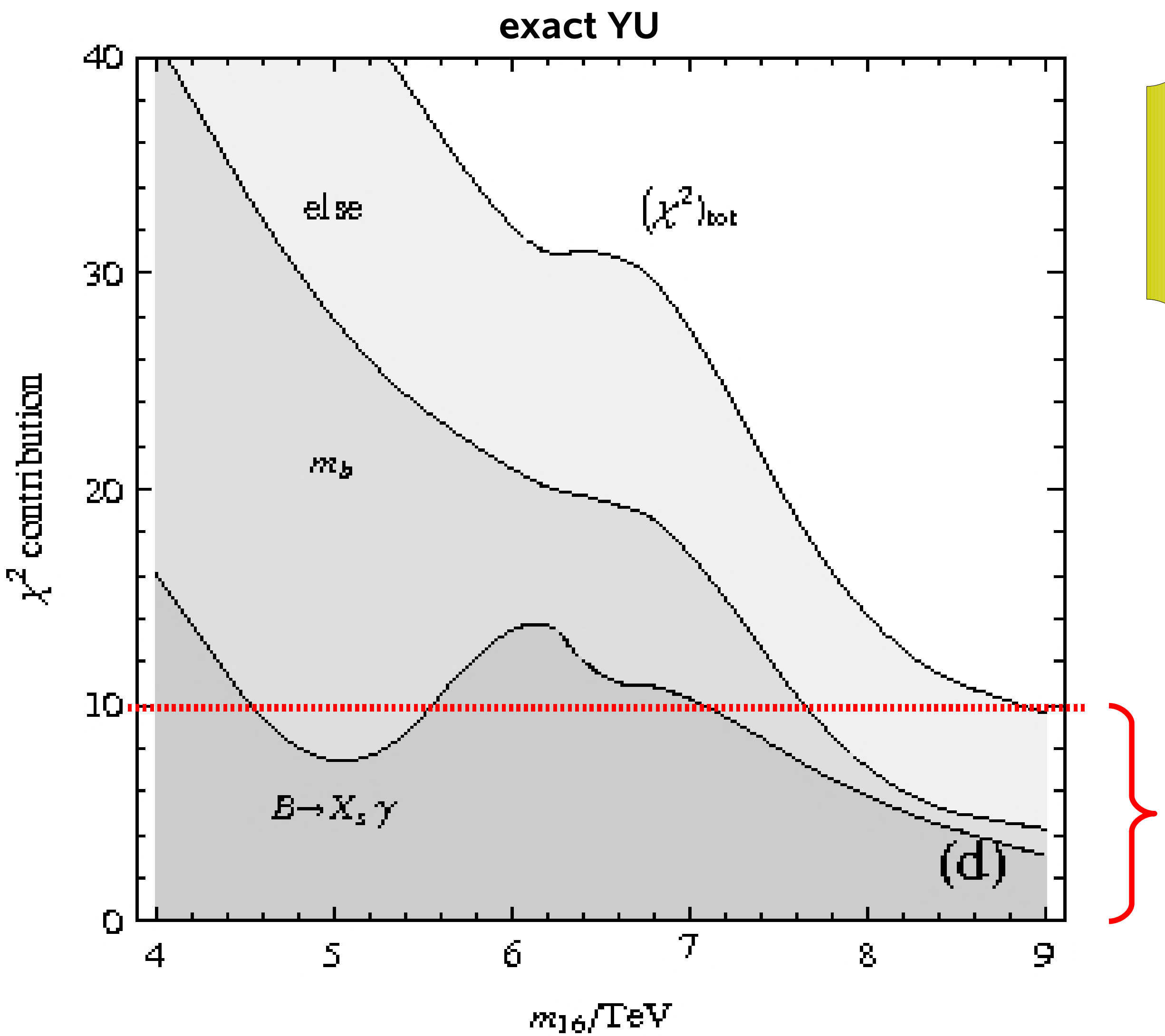
Lowering tanβ: Complete YU $\xrightarrow{\text{relaxed to}}$ $Y_t \simeq Y_\nu$ and $Y_b \simeq Y_\tau$

To address them,
one can study a *generic* SUSY GUT with universal soft terms as a function of

- tanβ: ruling the *required* breaking of top-bottom YU
- m_{16}: scale ruling the decoupling of the scalar sector

Results: Question 1

Is the above mentioned tension among FCNCs for tanβ O(50)
a general feature of SUSY GUTs with exact YU and universal GUT-scale soft terms ?



Main comment

For any $m_{16} \lesssim 9$ TeV, agreement among FCNCs is only achieved at the price of decoupling in the scalar sector

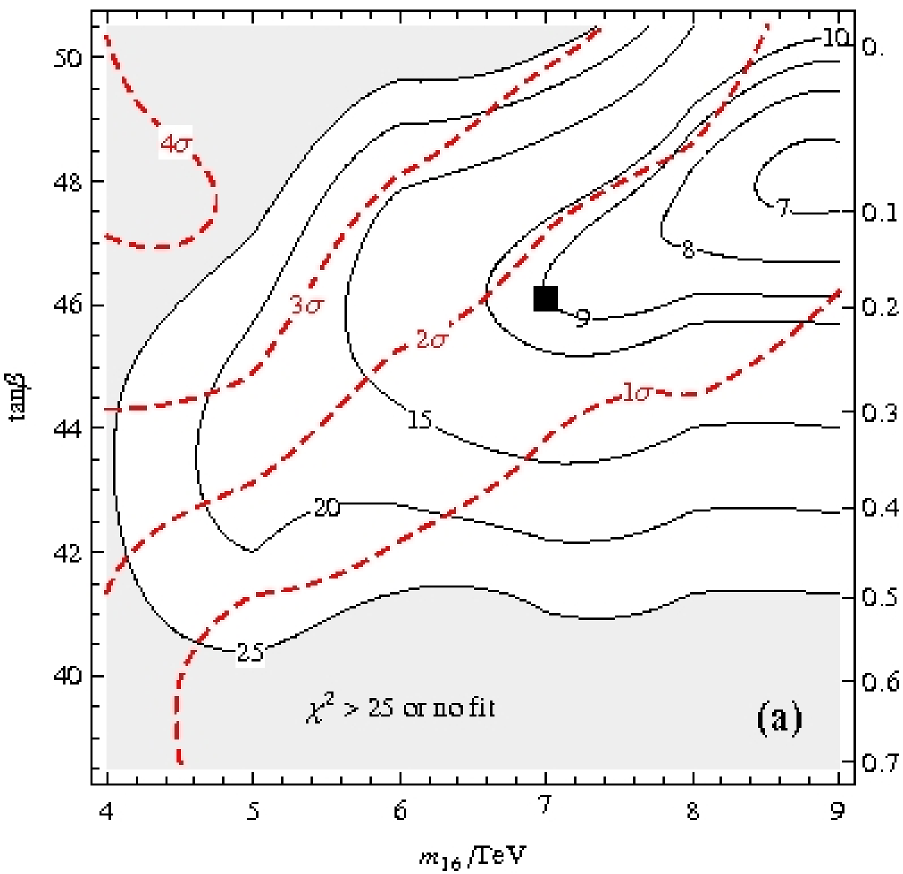
Disclaimer:
Needless to say, this test cannot be attached a statistically rigorous meaning

Results: Question 2

Is this tension relieved if tanβ is below 50
i.e. with YU relaxed to $Y_t \simeq Y_\nu$ and $Y_b \simeq Y_\tau$?

- **solid black line**: lines of constant χ^2
- **red dashed line**: lines of constant pull, with $\sigma \equiv \sqrt{\sigma^2_{\exp} + \sigma^2_{\rm theo}}$

$\sigma = B \to X_s \gamma$ pull



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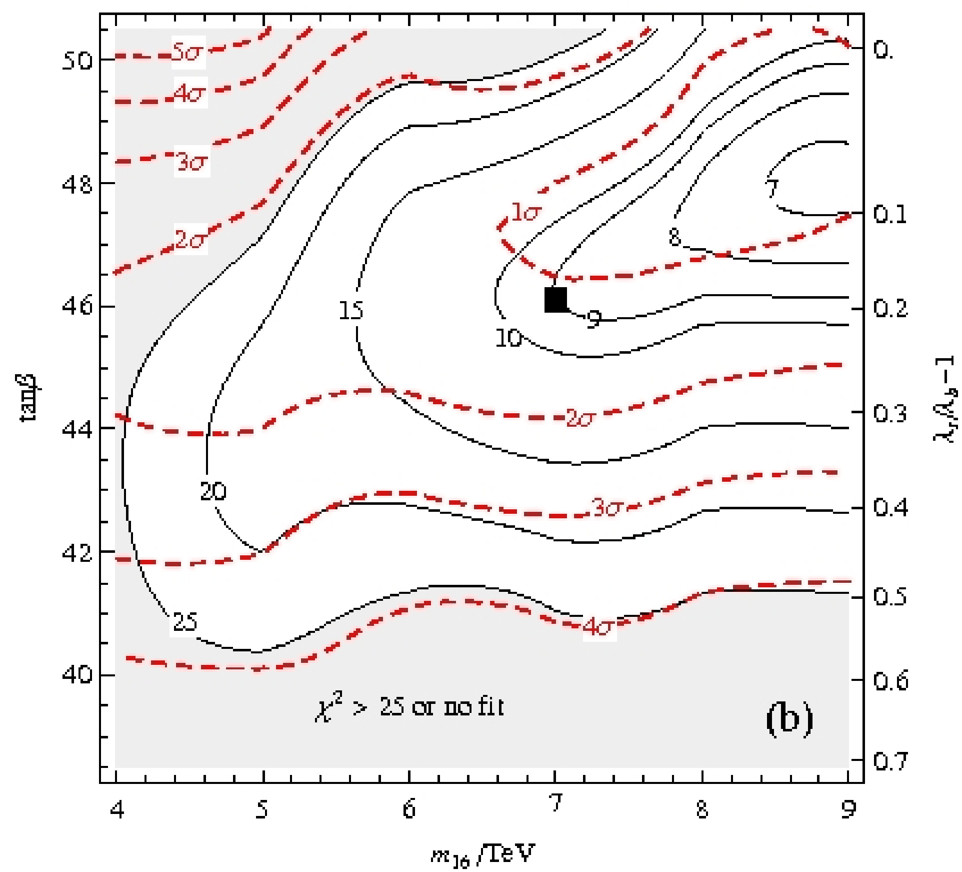

Results: Question 2

Is this tension relieved if $\tan\beta$ is below 50
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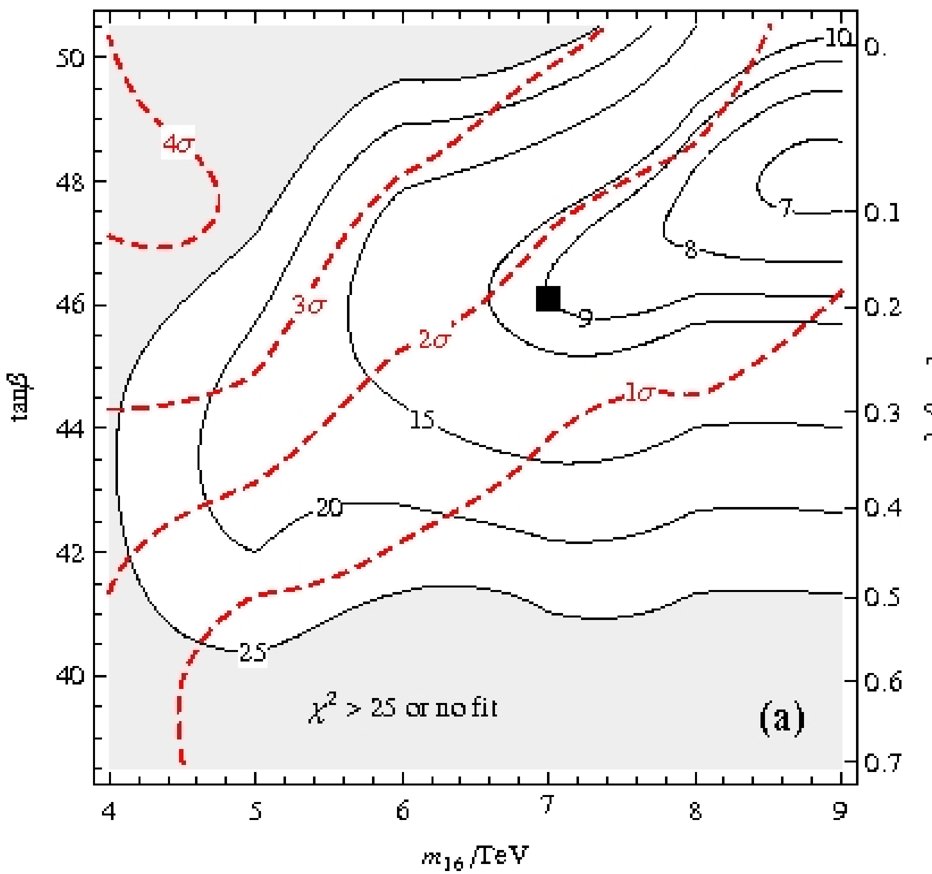

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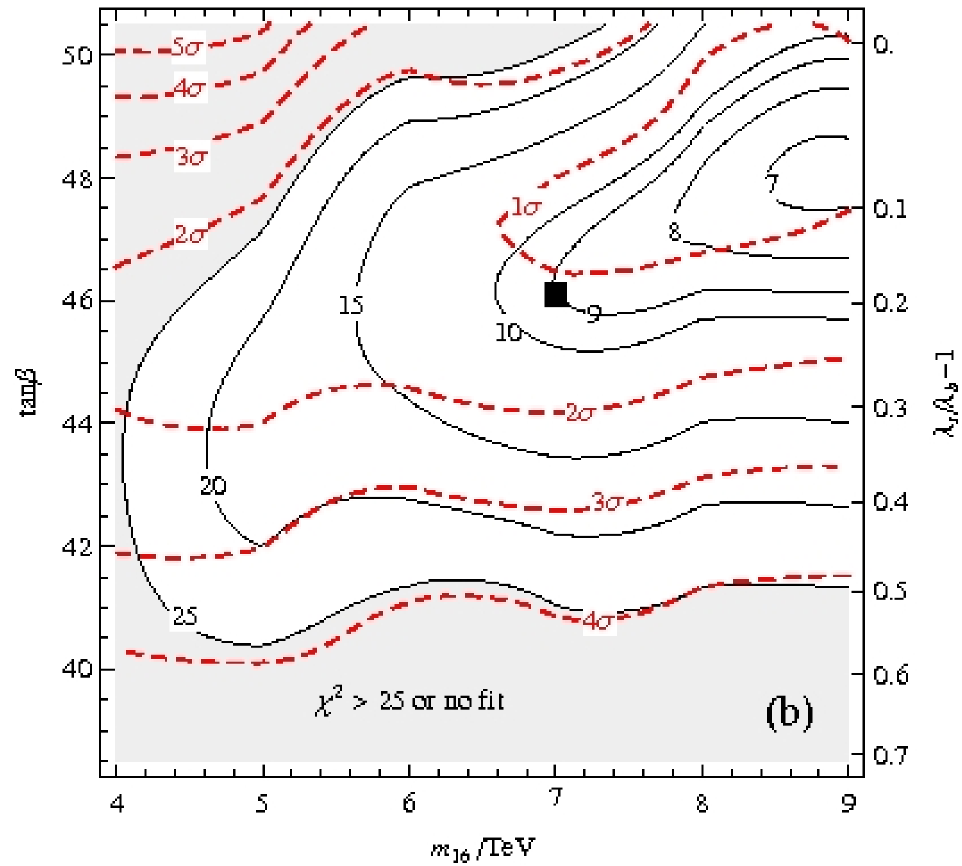

A region of successful fits exists
for $m_{16} \geq 7$ TeV and $46 \leq \tan\beta \leq 48$

$\Rightarrow$ moderate breaking of $t - b$ unification

- ☑ Non-trivial compromise between m_b and FCNCs
- ☑ (Light part of) SUSY spectrum basically fixed. E.g. lightest stop $\approx$ 800 GeV

Conclusions

1. Go/No-go message

Assuming GUT-scale universalities for the soft SUSY-breaking terms,
YU is phenomenologically viable only invoking decoupling of the sfermion spectrum.

Else, viability is recovered without decoupling if YU is broken to separate $t - \nu$ *and* $b - \tau$ *YU.*
This breaking must be moderate, O(10-20%)

These conclusions are the result of two non-trivial interplays:

- *One among FCNCs, mostly the decays* $B_s \to \mu^+ \mu^-$, $B \to X_s \gamma$ *and* $B \to X_s \ell^+ \ell^-$
- *One between (mostly)* $B \to X_s \gamma$ *and the bottom mass*

2. Is the moderate-breaking scenario falsifiable ?

Yes. The requirement of $b-\tau$ *unification & the cross fire of the* m_b *and FCNC constraint allow for robust predictions for the lightest SUSY spectrum and various FCNCs*

Observable	Exp.	Fit	Pull
M_W	80.403	80.56	0.4
M_Z	91.1876	90.73	**1.0**
$10^5\ G_\mu$	1.16637	1.164	0.3
$1/\alpha_{em}$	137.036	136.5	0.8
$\alpha_s(M_Z)$	0.1176	0.1159	0.8
M_t	170.9	171.3	0.2
$m_b(m_b)$	4.20	4.28	**1.1**
M_τ	1.777	1.77	0.4
10^4 BR$(B \to X_s\gamma)$	3.55	2.72	**1.6**
10^6 BR$(B \to X_s\ell^+\ell^-)$	1.60	1.62	0.0
$\Delta M_s/\Delta M_d$	35.05	32.4	0.7
10^4 BR$(B^+ \to \tau^+\nu)$	1.41	0.726	**1.4**
10^8 BR$(B_s \to \mu^+\mu^-)$	< 5.8	3.35	–
		total χ^2:	**8.78**

Input parameters		Mass predictions	
m_{16}	7000	M_{h^0}	121.5
μ	1369	M_{H^0}	585
$M_{1/2}$	143	M_A	586
A_0	-14301	M_{H^+}	599
$\tan\beta$	46.1	$m_{\tilde{t}_1}$	783
$1/\alpha_G$	24.7	$m_{\tilde{t}_2}$	1728
$M_G/10^{16}$	3.67	$m_{\tilde{b}_1}$	1695
$\epsilon_3/\%$	-4.91	$m_{\tilde{b}_2}$	2378
$(m_{H_u}/m_{16})^2$	1.616	$m_{\tilde{\tau}_1}$	3297
$(m_{H_d}/m_{16})^2$	1.638	$m_{\tilde{\chi}^0_1}$	58.8
$M_R/10^{13}$	8.27	$m_{\tilde{\chi}^0_2}$	117.0
λ_u	0.608	$m_{\tilde{\chi}^+_1}$	117.0
λ_d	0.515	$M_{\tilde{g}}$	470

TABLE IV: Example of successful fit in the region with $b-\tau$ unification. Dimensionful quantities are expressed in powers of GeV. Higgs, lightest stop and gluino masses are pole masses, while the rest are running masses evaluated at M_Z.

Discovering or excluding this scenario will be within reach of the LHC

Conclusions

3. Topics for the final discussion

(a) *It would be useful if Atlas / CMS considered also viable Yukawa-unified GUT scenarios in production runs.*

These scenarios are not less compelling than the CMSSM
and spectrum files in the viable regions are available

- A useful study of the LHC prospects for these scenarios has been presented in Baer, Kraml, Sekmen, Summy, JHEP 08.

  ➡ Starting point for production runs including hadronization & detector effects

  (We are also taking steps in this direction with Atlas colleagues in Munich)

(b) Difficult to overemphasize the importance of an *accurate* determination of
BR[$B_s \to \mu^+ \mu^-$] (LHCb and Atlas / CMS) and BR[$B \to \tau \nu$] (Super Flavor Factory)

Backup Slides

Detailed chart of the fitting procedure