SUSY GUTs with Yukawa unification in the light of data

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Based on:

DG, Raby, Straub (JHEP 09)

Altmannshofer, DG, Raby, Straub (PLB 08)

Albrecht, Altmannshofer, Buras, DG, Straub (JHEP 07)

+ work in preparation.

Introductory remarks

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

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

☐ 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:

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

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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Predicted pattern of SUSY masses
needs specification of

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- *the form Yukawa couplings have at the high scale*

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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

3^{rd} generation Yukawa unification (YU)

YU depends:

– on $\tan\beta$ being large, O(50).

– on the details of the SUSY spectrum, since YU receives EW-scale threshold corrections, growing with growing $\tan\beta$

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:

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

These relations automatically lead to "Inverted Scalar Mass Hierarchy":

1-2-3 hierarchy for fermions vs.
3-2-1 hierarchy for sfermions.

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Bagger et al.

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Can one perform a deeper test of the YU parameter space?

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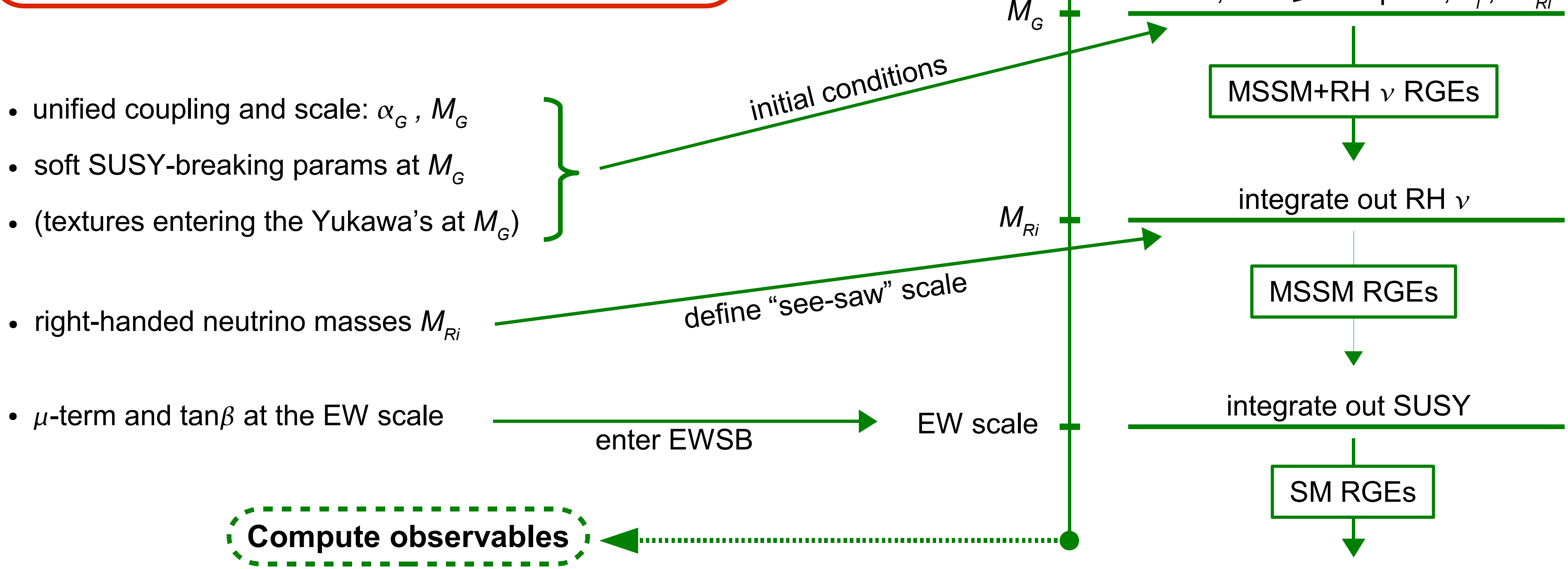
One step back:
how a GUT-scale model is tested at the EW scale



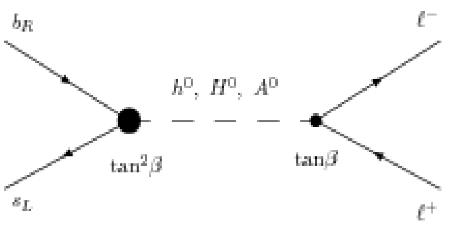
The two crucial FCNCs: $B_s \to \mu^+\mu^-$ vs. $B \to X_s \gamma$

A generic expectation in YU is large tanβ

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

☑ $BR[B_s \to \mu^+\mu^-]$

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

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

M_A > 500 GeV

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

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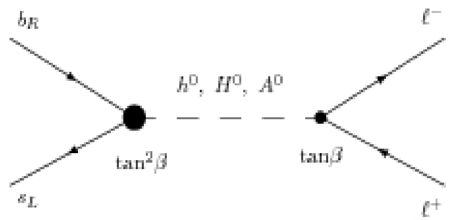

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☑ BR[$B \to X_s\,\gamma$]

$$\mathrm{BR}[B \to X_s\gamma]^{\mathrm{exp}}_{E_\gamma > 1.6\,\mathrm{GeV}} = (3.52 \pm 0.25) \times 10^{-4}$$ { 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"

☑ $BR[B \to X_s \gamma]$ [continued]

Very rough formula

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

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

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

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

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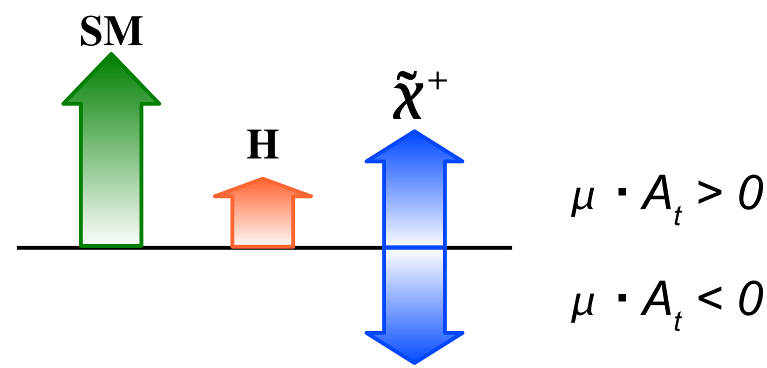
Main features

- 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 $B_s \to \mu^+ \mu^-$

- Contributions from charginos are the dominant ones, and behave like

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



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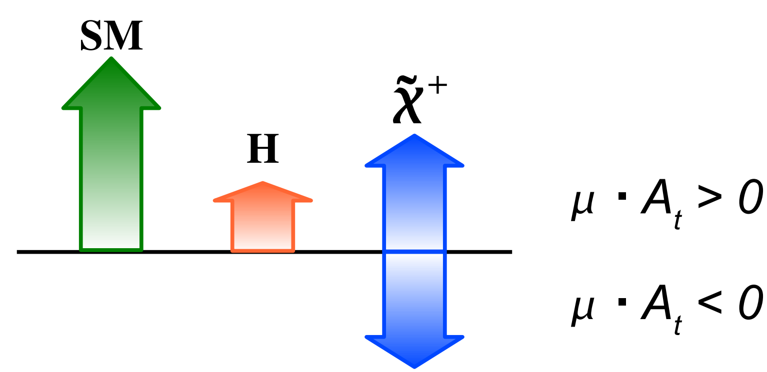
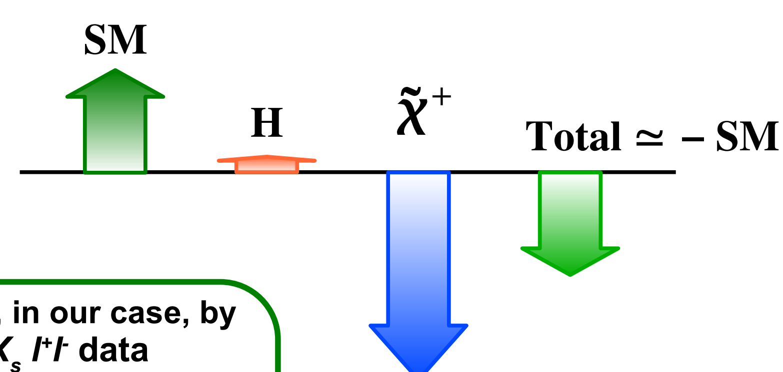


Specifically, chargino contrib's can be very large. As a matter of fact, for m_{16} < 4.5 TeV:

$$\mu\cdot A_t < 0$$

"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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Consequences

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*

Altmannshofer, D.G., Raby, Straub

Question up to now:

Take SUSY GUTs with soft-terms universalities.
To which extent is the hypothesis of Yukawa Unification viable ?

Answer: one needs to invoke either decoupling
or a (moderate, 10-20%) breaking of YU

Question now:

Stick to SUSY GUTs where YU is <u>exact.</u>
Are there soft-terms non-universalities that:

- can be meaningfully motivated in terms of the underlying mechanism of SUSY breaking ?
- lead to phenomenological viability <u>without decoupling</u> ?

Two simple scenarios of non universalities emerge:

- non-universal gaugino masses

  widely studied, see e.g. Baer *et al.*, Balazs, Dermisek

- non-universal soft terms of “minimal flavor violating” (MFV) form, i.e. inheriting from the Yukawa couplings present in the SM

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MFV parameterization

Soft terms become functions of the Yukawa couplings, the functional form being dictated by spurion symmetry (Yukawa's as the only sources of flavor-symmetry breaking)

Main point here

It is clear that the hypothesis of Yukawa Unification – and the hierarchical structure of Yukawa's – amounts to a drastic simplification of the soft-terms parameterization

For example, from the general MFV expansions of squark soft terms:

$$
\begin{aligned}
m_Q^2 &= \overline{m}_Q^2(\mathbb{1} + c_Q^u Y_U Y_U^\dagger + c_Q^d Y_D Y_D^\dagger + O(Y_{U,D}^4))\ ,\\
m_U^2 &= \overline{m}_U^2(\mathbb{1} + c_U^u Y_U^\dagger Y_U + O(Y_U^4))\ ,\\
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\end{aligned}
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Yukawa Unification and Yukawa hierarchies imply that these soft masses can be parameterized in terms of:

- ✓ Scale for *Q, U, D* bilinears **= 3 real parameters**
- ✓ Y_{top} driven splitting of 3rd gen. *Q, U, D* bilinears **= 3 real parameters**
- ✓ Scale for top, bottom trilinears $\overline{A}_{U(D)}$ **= 2 complex parameters**

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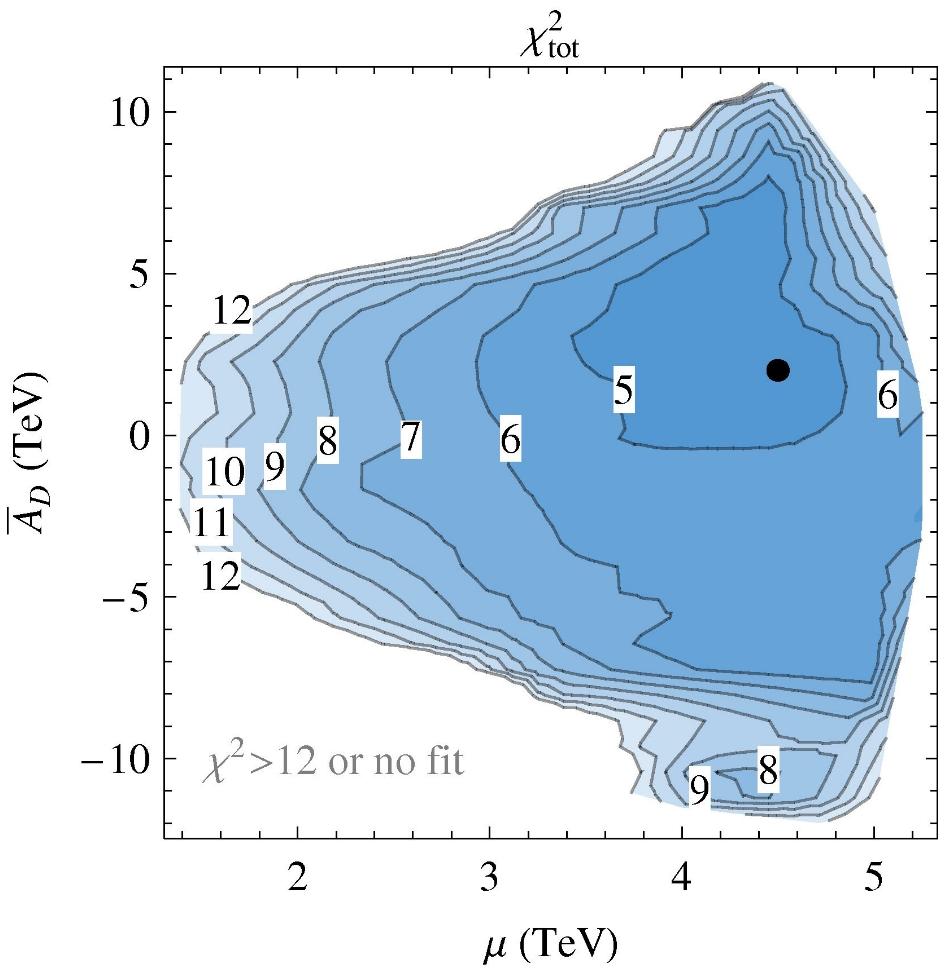
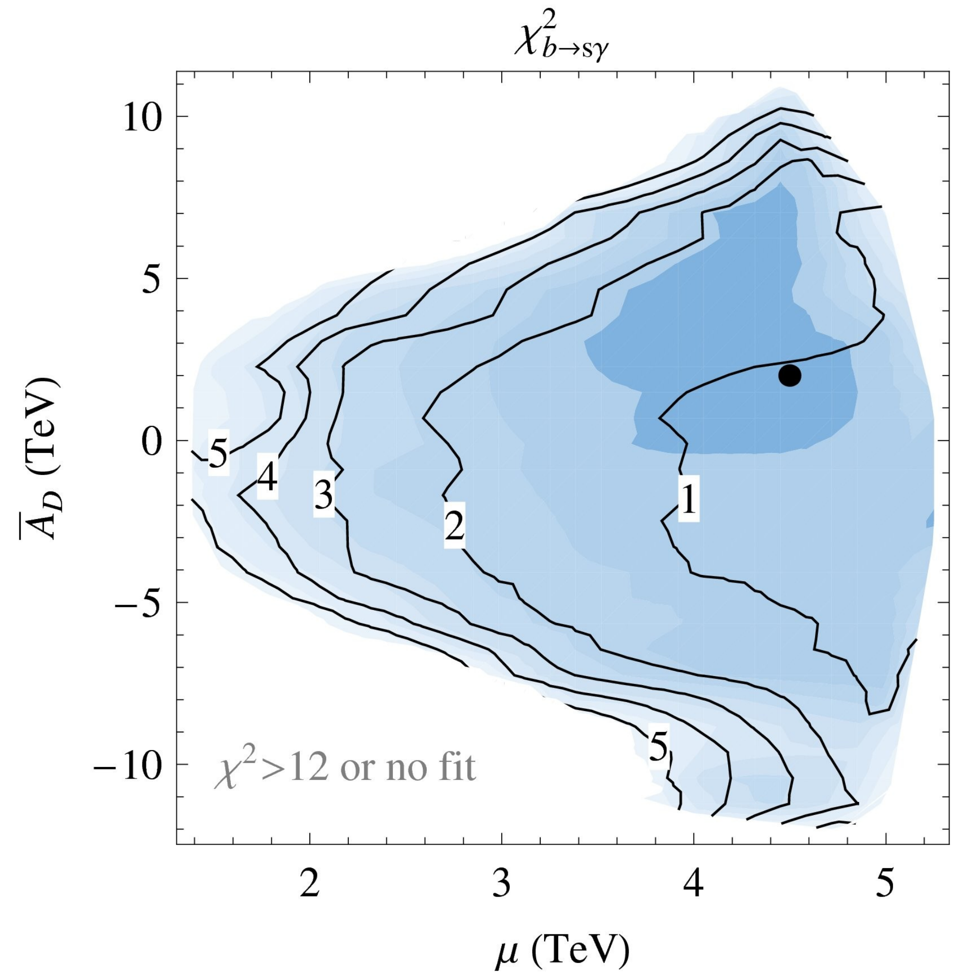
We will focus on the case of <u>trilinear splittings</u>

- bilinear splittings have already been (partly) explored, and look only partly promising
- our initial χ^2 explorations – with all the splittings allowed – pointed mostly to trilinear splittings

Global picture

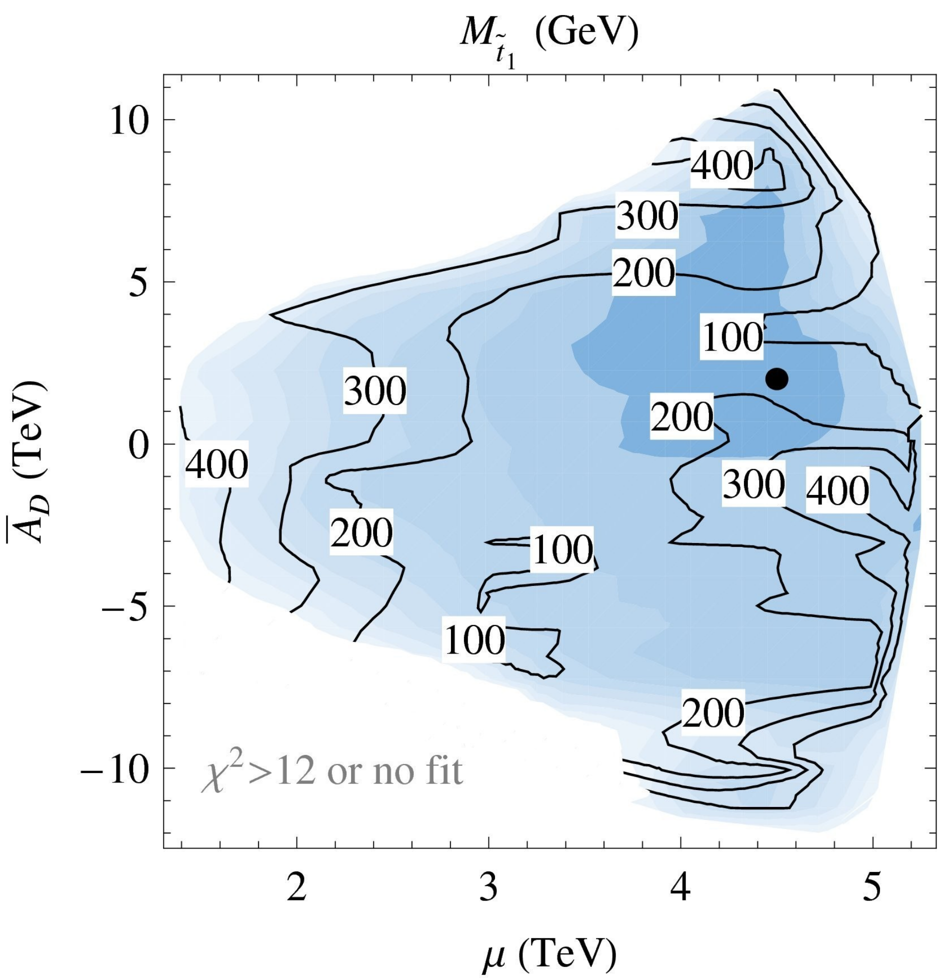


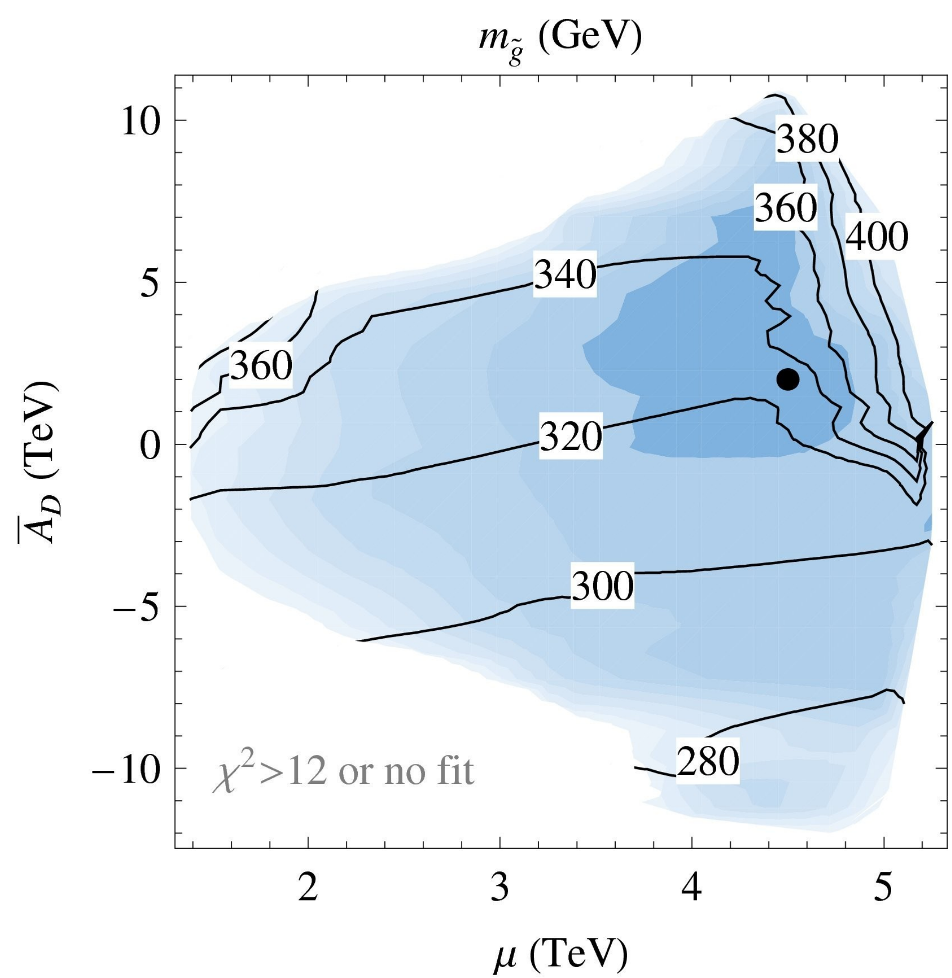


- $|\overline{A}_U - \overline{A}_D| \approx$ ***O(TeV)***
  with $\overline{A}_U \approx -2.5\ m_{16}$
- ***for too large*** μ***, the*** χ^2 ***starts deteriorating again***

- ***large*** $\mu \approx$ ***O(***m_{16}***)***
  (mostly driven by b → s γ**)**

Spectrum: main features





- ***veeery light lightest stop mass***

- ***the gluino mass is correlated with $\overline{A}_D$ (2-loop RGE effect)***

  (hence a measurement of the former would give insights on the latter)

Comments on the spectrum

Main conclusion: *the recovery of phenomenological viability is not obtained by invoking decoupling of the scalar sector.*

It instead strongly <u>requires</u> part of the spectrum, e.g. the lightest stop, to be close to the experimental lower bound.

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Main spectrum features

- *Lightest stop mass $\approx$ 100 – 200 GeV (i.e. amazingly light)*

Most striking difference with respect to the scenario with YU breaking

- *Gluino mass $\approx$ 350 GeV*
- *Lightest chargino and neutralino masses as light as allowed by experiment*
- *Lightest Higgs mass comfortably above the LEP bound*
- *Heavy Higgses at around 1 TeV*
- *Rest of the spectrum $\approx$ $O(m_{16})$ for good reasons*
  [lack of a large Yukawa coupling (1st and 2nd generation sfermions) or because $\mu \approx O(m_{16})$ (charginos and neutralinos)]

Summarizing

We have analysed, in the light of existing collider data, two scenarios of Yukawa-unified SUSY GUTs, fairly complementary to each other:

- a scenario with *universalities in the soft terms* for gauginos and sfermions:

  ⇨ one needs a moderate breaking of Yukawa Unification

- a scenario where *Yukawa Unification is kept exact*, relaxing instead the (poorly motivated) assumption of soft-terms universalities. Focusing on minimally flavor violating soft terms:

  ⇨ data point to a scenario with large mu term and a splitting in the trilinear soft terms. This parameter space leads to a very light lightest stop.

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➡ **Sharp predictions for the lightest part of the SUSY spectrum**

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We have found that the cross-fire of the constraints makes the viable parameter space highly specific. ➡ **Sharp predictions for the lightest part of the SUSY spectrum**

Next step to take

<u>Given the specificity of the spectrum predictions</u>, can one work out a strategy to single out (or exclude) the two mentioned scenarios using LHC data ?

Answer: work in progress [blackboard details]

Backup Slides

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:

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

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,
- $B_s \to \mu^+ \mu^-$

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

$$\boldsymbol{Y_{u,d}} = \textbf{diag}\{\mathit{0},\, \mathit{0},\, \lambda_{u,d}\}$$

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

Detailed predictions within the scenario of moderate-breaking of Yukawa Unification

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
$1/\alpha_{\rm em}$	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
$10^4\ {\rm BR}(B \to X_s \gamma)$	3.55	2.72	**1.6**
$10^6\ {\rm BR}(B \to X_s \ell^+ \ell^-)$	1.60	1.62	0.0
$\Delta M_s / \Delta M_d$	35.05	32.4	0.7
$10^4\ {\rm BR}(B^+ \to \tau^+ \nu)$	1.41	0.726	**1.4**
$10^8\ {\rm BR}(B_s \to \mu^+ \mu^-)$	< 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	$m_{\tilde\chi_1^0}$	58.8
$M_R/10^{13}$	8.27	$m_{\tilde\chi_2^0}$	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.

Effective parameterization of MFV in the case of YU

Starting from the MFV expansions:

$$\begin{cases} m_Q^2 = \overline{m}_Q^2(\mathbb{1} + c_Q^u Y_U Y_U^\dagger + c_Q^d Y_D Y_D^\dagger + O(Y_{U,D}^4)) \,, \\ m_U^2 = \overline{m}_U^2(\mathbb{1} + c_U^u Y_U^\dagger Y_U + O(Y_U^4)) \,, \\ m_D^2 = \overline{m}_D^2(\mathbb{1} + c_D^d Y_D^\dagger Y_D + O(Y_D^4)) \,, \\ A_U = \overline{A}_U Y_U(\mathbb{1} + O(Y_D^2)) \,, \\ A_D = \overline{A}_D Y_D(\mathbb{1} + O(Y_U^2)) \,, \end{cases}$$

the hypothesis of YU, and the hierarchical structure of the Yukawa couplings, allow to drastically simplify these expansions.

Soft terms in the previous expansions are in fact easily seen to fulfill the approximate patterns

$$m_{Q,U,D}^2 \simeq \begin{pmatrix} \overline{m}_{Q,U,D}^2 & 0 & 0 \\ 0 & \overline{m}_{Q,U,D}^2 & 0 \\ 0 & 0 & \overline{m}_{Q,U,D}^2 + \Delta m_{Q,U,D}^2 \end{pmatrix} ,$$

$$A_{U(D)} \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_{t(b)} \overline{A}_{U(D)} \end{pmatrix} ,$$

valid up to terms of order $(Y_{U,D}^2)_{ij}/y_{33}^2$

Why A-term splitting helps YU

Recall: *to suppress gluino contributions (positive) to m_b,*

one needs a large trilinear term for the stop (to enhance chargino contributions)

AND

a $m_{stops} \ll m_{sbottoms}$ hierarchy

the latter is greatly helped by $|\overline{A}_D| \ll |\overline{A}_U|$

ruling $m_{\tilde{t}_2} \approx m_{\tilde{b}_1}$

ruling $m_{\tilde{t}_1}$

ruling $m_{\tilde{b}_2}$

$$(m^2_{\tilde{Q}})_{33} \approx 0.51\, m^2_{16} - 0.12\, m^2_{H_u} - 0.09\, m^2_{H_d} - 0.02\, \overline{A}^2_U - 0.02\, \overline{A}^2_D$$

$$(m^2_{\tilde{U}})_{33} \approx 0.49\, m^2_{16} - 0.22\, m^2_{H_u} - 0.01\, m^2_{H_d} - 0.06\, \overline{A}^2_U + 0.01\, \overline{A}^2_D$$

$$(m^2_{\tilde{D}})_{33} \approx 0.55\, m^2_{16} + 0.01\, m^2_{H_u} - 0.21\, m^2_{H_d} + 0.01\, \overline{A}^2_U - 0.05\, \overline{A}^2_D$$

Note:
m^2_U goes down if
$\overline{A}_D$ is smaller

Hence $|\overline{A}_D| \ll |\overline{A}_U|$ *helps the hierarchy* $(m^2_{\tilde{U}})_{33} \ll (m^2_{\tilde{Q}})_{33} < (m^2_{\tilde{D}})_{33}$

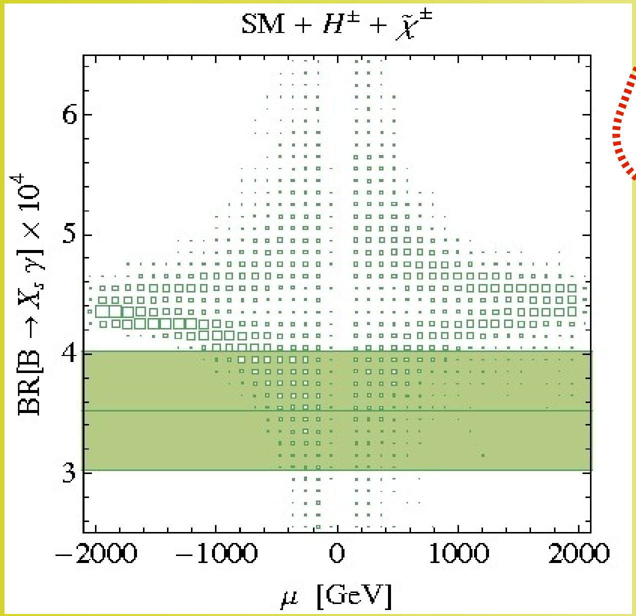
$$\Rightarrow \quad m_{\tilde{t}_R} \ll m_{\tilde{t}_L} \approx m_{\tilde{b}_L} < m_{\tilde{b}_R}$$

Why large μ

Recall: $\Delta m_b = \Delta_{\rm gluino} + \Delta_{\rm chargino} < 0$ *thanks to the trilinear-splitting mechanism*

Since both corrections are proportional to μ,
large μ triggers the right size for the total correction Δm_b

In addition: *large μ suppresses the chargino contributions to $b \to s\,\gamma$,*
thus preventing a large destructive interference with the SM contribution



Plot and discussion in **Wick, Altmannshofer, SUSY08 procs.**

Note also: *for too large μ, the negative correction to m_b becomes too large in magnitude,*
so that the mechanism has to be tamed somehow.