# Yukawa unification in extended GMSB models

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extended GMSB: GMSB + messenger superpotential couplings

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- messenger-matter mixing &  $y_{t,b,\tau}$  running
- $y_t y_b y_\tau$  unification in  $SO(10)$  inspired model

## 1. LHC vs. MSSM

What do the LHC searches tell us about MSSM?

- no SUSY signal so far
- relevant exclusions only for 1st and 2nd family
- still  $\widetilde{Q}_3, \ldots$  can be as light as 500 GeV



ATLAS-CONF-2013-047

signal cross-section by the the[o](#page-0-0)retical scale and PDF uncertainties. Previous results for *m*χ˜<sup>0</sup>

<span id="page-2-0"></span> $\equiv$   $\Omega Q$ 

= 0 obse[rve](#page-23-0)d limits obtained by varying the

the 1st experimental and background-theor[y u](#page-1-0)[nce](#page-3-0)[rta](#page-1-0)[int](#page-2-0)[ie](#page-3-0)[s o](#page-0-0)[n th](#page-23-0)[e](#page-0-0) [m](#page-0-0)aterial and properties on the material and material

indicated by solid curves. The dotted lines represent the *m*χ˜<sup>0</sup>

#### 2. Limits on stop mass



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## 3. LHC vs. MSSM

What do the LHC searches tell us about MSSM?

- Squark-gluino-neutralino model squark mass [GeV] **ATLAS** Preliminary .<br>m(χ  $S_{\text{1}}$ ) = 0 GeV Observed limit (±1 σ $\frac{\sigma_{\text{2}}}{\sigma_{\text{1}}}\frac{1}{\sigma_{\text{2}}}\left(1+\frac{1}{\sigma_{\text{2}}}\right)$  $0.2600$ ) theory no SUSY signal so far <sup>∼</sup> m(  $\frac{1}{\sqrt{2}}$  = 0 GeV Expected limit (±1 σ $_{\rm exp}$ )<br> $\frac{2}{\sqrt{2}}$  = 395 GeV Observed limit fb<sup>1</sup>, fs=8 Te <sup>∼</sup> m( 2400 relevant exclusions only for 1st <sup>∼</sup> m( ) = 395 GeV Expected limit 0-lepton combined ) = 695 GeV Observed limit <sup>∼</sup> m( 2200 and 2nd family  $m(\tilde{\chi}^0) = 695 \text{ GeV}$  Expected limit 2000  $7 \text{TeV}$  (4.7fb<sup>-1</sup>) m $(\tilde{\chi}^0)$  = 0 GeV Observed • still  $\widetilde{Q}_3, \ldots$  can be as light as 1800 500 GeV 1600 <u> 1999 - Germania Santana</u> 1400 1200 1000  $800_{800}$ BUT important information comes 800 1000 1200 1400 1600 1800 2000 2200 2400 gluino mass [GeV] from Higgs mass measurement: ATLAS-CONF-2013-047
	- $m \sim 125 \text{ GeV} \rightarrow \text{need}$  for large loop corrections  $t_{\text{total}}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  common mass), with direct decays to  $\frac{1}{2}$

 $\alpha$  and  $\widetilde{a}$  is negative much heavier and masses of  $\widetilde{O}_1$  and  $\widetilde{a}$  are ASSUME other MSSM Higgses are much heavier and masses of  $Q_{1,2}$  and  $\tilde{g}$  are bigger than 1.8 TeV each point. The dashed lines show the expected limits at 95% CL, with the light (yellow) band indicating bigger than 1.8 TeV.

indicated by solid curves. The dotted lines represent the *m*χ˜<sup>0</sup>

<span id="page-4-0"></span>1 signal cross-section by the theoretical scal[e an](#page-3-0)d [P](#page-5-0)[D](#page-3-0)[F u](#page-4-0)[nc](#page-5-0)[erta](#page-0-0)[inti](#page-23-0)[es.](#page-0-0) [Pr](#page-23-0)[evi](#page-0-0)[ous r](#page-23-0)esults for *ma*ximum and PDF uncertainties. Previous results for *maximum and PDF uncertainties.* Previous results for *maximum and maximum* ATLAS at 7 TeV  $\sim$  7 TeV  $\sim$  [re](#page-0-0)presented by the shaded (light blue) are valid for  $\sim$ 

#### 4. 1-loop corrections to  $m_{h^0}$ Figure 4. 1-loop corrections to  $m_{h^0}$ Oscillations along the shallow direction, with H<sup>0</sup>  $\frac{10}{10}$

dominant contribution from top quarks and stops (due to  $y_t \sim 1$ ): the orthogonal steeper direction corresponds to the mass eigenstate H0.

$$
\Delta(m_{h^0}^2) = \frac{h^0}{2} - \left(\bigodot_{i=1}^t -1 \right) - \frac{h^0}{2} - \left(\bigodot_{i=1}^t -1 \right) - \frac{h^0}{2} -
$$

$$
m_{h^0}^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \left[ \ln \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} \left( 1 - \frac{X_t^2}{12M_S^2} \right) \right] \approx (125 \,\text{GeV})^2,
$$

inequality (7.23) were robu[s](#page-0-0)t, the lightest Higgs boson of the MSSM would have been discovered at  $\alpha$ 

will see . We have characterized the scale of superpart- $\mathbf{r} = \mathbf{r} - \mathbf{r}$ 

 $A$ -terms:  $\mathbf{I}$  we expect a mild  $\mathbf{I}$ 

$$
V_{\text{soft}} \supset y_t A_t H_u \widetilde{Q}_3 \widetilde{\overline{U}}_3 \longrightarrow y_t A_t h_0 \widetilde{t}_1 \widetilde{t}_2
$$

are the soft masses of the soft masses of the third-generation left-handed  $\alpha$ 



<span id="page-5-0"></span>only weakly dependent on the stop mass up to ∽ 5 TeV. The stop mass up to ∽ 5 TeV. The stop mass up to ∠ 5 TeV. solid curve is mh = 125 GeV with mt = 125 GeV with mt = 173.2 GeV. The band mt = 173.2 GeV. The band method of

<sup>d</sup> <sup>≈</sup> 10, correspond to the mass eigenstate <sup>h</sup>0, while

## 5. A-terms in GMSB

 $\bullet$  in GMSB models A-terms = 0 at messenger scale



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pletely set in stone, and it would be interesting to look for

$$
\mu \frac{dA_t}{d\mu} \sim y_t^2 A_t + g_3^2 M_3
$$

- 3.5  $\bullet$  hard to reconcile
	- $m_{h0} \gtrsim 123 \,\text{GeV}$
	- pure GMSB mechanism

requires scalar masses in the range of 5 to 10 TeV.

<span id="page-6-0"></span>dating a 125 Ge[V H](#page-5-0)i[ggs](#page-7-0) [in](#page-5-0) [the](#page-6-0)[MSS](#page-0-0)[M](#page-23-0) [with](#page-0-0) [sm](#page-23-0)[all](#page-0-0) A[-te](#page-23-0)rms in the MSSM with small A-terms in the MSSM w

- light stops
- 1.0 1.2 1.4 1.6 1.8  $M_{\widetilde{g}} \lesssim 2.5 \, \mathrm{GeV}$

• large A-terms at  $M$ ?

#### 6. How to generate large  $A$ -terms?  $\mathbf{0}$ . <sup>1</sup> !TeV"

*mt* !

value of  $A$ -term gives initial condition for RGE evolution Fig. 3. Contour plot of  $\mathbf{0}$ 



 $\mu \frac{dA_t}{d\mu} \sim y_t^2 A_t + g_3^2 M_3$ 

 $\bullet$  heavy  $\widetilde{q}$  and RGE evolution from  $M \ge 10^{14}$  GeV

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 $\bullet$  or large A-terms at M

 $\mathbf{F}_{\mathbf{r}}$  at left, in a case where  $\mathbf{F}_{\mathbf{r}}$  is large and negative at right, in a case where  $\mathbf{F}_{\mathbf{r}}$ Draper et al. 1112.3068

 $\bullet$  how to get A-terms in GUT model?

(as defined e.g. in [25]), the A-terms are strictly zero at the messenger scale. This conclusion remains robust even

This has important consequences for models of gauge Extended GMSB models (EGMSB)

## 7. SUSY breaking mediation



• singlet 
$$
\langle X \rangle = M + \theta^2 F \rightarrow
$$
 spontaneous SUSY breaking

$$
\xi = \frac{F}{M} \sim 10^5 \,\mathrm{GeV}
$$

- messengers have large masses e.g.  $M \sim 10^8 10^{14}$  GeV
- mediation = interactions between  $Y, \overline{Y}$  and other fields
- $\bullet$  assumption: all messengers couple to the spurion X in the same way

$$
XY_a\overline{Y}_a
$$

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and  $M \gtrsim 10^8 \text{ GeV} \longrightarrow 1\text{-loop}$  soft masses negligi[ble](#page-7-0)

#### 9. Trilinear terms in EGMSB models

$$
W = \frac{1}{6}y_{abc}\Phi_a\Phi_b\Phi_c + \frac{1}{2}h_{ab}\Phi_a\Phi_b\mathsf{Y} + h_a\Phi_a\mathsf{Y}\mathsf{Y} + \eta\mathsf{Y}\mathsf{Y}\mathsf{Y}
$$



$$
V \supset T_{abc} \widetilde{\Phi}_a \widetilde{\Phi}_b \widetilde{\Phi}_c, \qquad T_{abc} = -\frac{\xi}{16\pi^2} \left[ C_a h_{ad} h_{de}^* y_{ebc} + \ldots \right] + (a \leftrightarrow b) + (a \leftrightarrow c)
$$

 $\bullet$   $T_{abc}$  are 'partially aligned' to MSSM Yukawas  $y_{abc}$ 

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## 10. A-terms in EGMSB models

$$
V \supset H_u \widetilde Q(T_u) \overline{\widetilde U} + H_d \widetilde Q(T_d) \overline{\widetilde D} + H_d \widetilde L(T_e) \overline{\widetilde E}
$$

• 
$$
(T_{u,d,e})_{33} =: y_{t,b,\tau} A_{t,b,\tau}
$$
  
\n
$$
A_{t,b,\tau} \approx -\frac{\xi}{16\pi^2} C^{(t,b,\tau)} |h|^2 \qquad \text{e.g. } C^{(t,b,\tau)} = 10, 12, 11
$$

A-terms

- relevant to the  $m_{h^0}$
- may also lead to CCB when

$$
A_f^2 > 3(m_{\tilde{f}_L}^2 + m_{\tilde{f}_R}^2 + \mu^2 + m_{H_u}^2)
$$

• affect sfermion masses  $m_{\tilde{f}_{1,2}}$ 

$$
(\widetilde f_L^*\ \widetilde f_R^*) \left(\begin{array}{cc} m^2_{\tilde f_{LL}} & m_f (A_f - \mu \tan\beta^{\pm 1}) \\ m_f (A_f - \mu \tan\beta^{\pm 1}) & m^2_{\tilde f_{RR}} \end{array}\right) \left(\begin{array}{c} \widetilde f_L \\ \widetilde f_R \end{array}\right)
$$

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 $\rightarrow \tilde{f}_1$  may be tachyonic

#### 11. Soft masses in EGMSB models

2-loop contributions to soft masses

 $W_Y = h^{(1)}\Phi YY + h^{(11)}\Phi \Phi Y$ 



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#### 12. 2-loop soft masses induced by  $YYY$

$$
W_Y = h_i^{(I)} \Phi_i YY + h_{ij}^{(II)} \Phi_i \Phi_j Y + \eta YYY
$$



Remark:  $\eta$  are relevant only if a model contains both  $5+\overline{5}$  and  $10+\overline{10}$  messengers

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#### 13. Kinetic mixing

• fields Y,  $\phi$  with the same charges can mix:  $\phi \leftrightarrow Y$ 

$$
Q \leftrightarrow Y_Q, \overline{U} \leftrightarrow Y_{\overline{U}}, \dots \quad \text{(in some models: } H_d \leftrightarrow L \leftrightarrow Y_L)
$$

• superpotential and Kähler potential K at scale  $t = \log \mu$ 

$$
W = \frac{1}{6}\lambda_{ijk}\Phi_i\Phi_j\Phi_k + \frac{1}{2}M_{ij}\Phi_i\Phi_j, \quad K = \Phi_i^{\dagger}Z_{ij}(t)\Phi_j, \quad Z = Z^{\dagger}, Z > 0
$$

couplings  $\tilde{\lambda}(t)$  and masses of <u>canonically</u> normalized fields  $\tilde{\Phi}_i = Z_{ij}^{-1/2} \Phi_j$ 

$$
\widetilde{\lambda}_{ijk}(t) = \lambda_{i'j'k'} Z_{i'i}^{-1/2} Z_{j'j}^{-1/2} Z_{k'k}^{-1/2}, \quad \widetilde{M}_{ij}(t) = M_{i'j'} Z_{i'i}^{-1/2} Z_{j'j}^{-1/2}
$$

RGE evolution of Z (re)introduces mixing mass terms!  $\bullet$ 

e.g.

$$
W = \widetilde{M}_1 \widetilde{Y}_R \widetilde{Y}_{\overline{R}} + \widetilde{M}_2 \widetilde{\phi}_R \widetilde{Y}_{\overline{R}} + \dots
$$

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important for decouplings and running Yukawa (couplings between light states)!

#### 14. Decoupling and running

$$
W = \frac{1}{6}\lambda_{ijk}\Phi_i\Phi_j\Phi_k + \frac{1}{2}M_{ij}\Phi_i\Phi_j, \quad K = \Phi_i^{\dagger}Z_{ij}(t)\Phi_j, \quad Z = Z^{\dagger}, Z > 0
$$

- method 1 rotate  $\Phi = Z^{-1/2} \Phi$  such that light fields are present
- method 2 instead of computing  $Z^{-1/2}$  and then rotating  $\Phi$  use Cholesky decomposition of Z:

$$
Z = V^{\dagger}V, \qquad \widetilde{\Phi} = \left(\begin{array}{c} \widetilde{\phi} \\ \widetilde{Y} \end{array}\right) = \underbrace{\left(\begin{array}{c} * & * \\ 0 & * \end{array}\right)}_{V} \left(\begin{array}{c} \phi \\ Y \end{array}\right)
$$

$$
\widetilde{\lambda}_{ijk}(t) = \lambda_{i'j'k'} V_{i'i}^{-1} V_{j'j}^{-1} V_{k'k}^{-1}
$$

 $\bullet$  one can check that

$$
\widetilde{\lambda}_{abc}(t) = \frac{\lambda_{abc}}{\sqrt{Z_{aa}Z_{bb}Z_{cc}}}, \quad \phi_a - \text{light fields}
$$

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#### 15. Evolution of Z from GUT scale  $t_{GUT}$

• RGE for  $Z(t)$  with boundary condition  $Z(t_{GUT}) = 1$ 

$$
\frac{d}{dt}Z_{ij} = -\frac{1}{8\pi^2} \left( \frac{1}{2} d_{kl} \lambda_{ikl}^* Z_{km}^{-1}{}^* Z_{ln}^{-1}{}^* \lambda_{jmn} - 2C_{ij}^{(r)} Z_{ij} g_r^2 \right)
$$

 $d_{kl}$  and  $C_{ij}^r$  - group theory factors

solve numerically or use approximate solution:

$$
Z_{ij}(t) = 1 + Z_{ij}^{(1)}(t - t_{GUT}) + \frac{1}{2!}Z_{ij}^{(2)}(t - t_{GUT})^2 + \dots
$$

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to compute  $Z^{(n)}$  one needs all  $Z^{(k)}$ ,  $k < n$ 

 $Z^{(n)}$  are expressed in terms of  $\epsilon = \ln 10/16\pi^2$ ,  $\lambda_{ijk}$ ,  $d_{kl}$ ,  $g_{GUT}$  and  $\beta_{g_r}(t_{GUT})$ 

16. Running of gauge couplings

$$
W = y_t H_u Q \overline{U} + h_t (H_u Q Y_{\overline{U}} + H_u Y_Q \overline{U}) + M (Y_U Y_{\overline{U}} + Y_Q Y_{\overline{Q}}) + \dots
$$



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## 17. Standard RGE vs. Z

$$
W = y_t H_u Q \overline{U} + h_t (H_u Q Y_{\overline{U}} + H_u Y_Q \overline{U}) + M (Y_U Y_{\overline{U}} + Y_Q Y_{\overline{Q}}) + \dots
$$

$$
y_t = 0.7, \ h_t = 0.4 \qquad \qquad y_t = 0.7, \ h_t = 0.9
$$

$$
y_t = 0.7, \ h_t = 0.9
$$



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## 18. SO(10) inspired GUT model

- at  $M_{GUT} \sim 10^{16} \text{GeV}$ :  $SO(10) \rightarrow SU(5) \times U(1)_x \rightarrow \ldots$
- $\bullet$  chiral matter  $\Phi$

 $H_{10}$  :  $10 \rightarrow 5_2 + \overline{5}_{-2}$ ,  $\phi_{16}$  :  $16 \rightarrow 10_{-1} + \overline{5}_3 + 1_{-5}$ 

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• mesengers 
$$
Y = (Y_{16}, Y_{16})
$$
  
\n
$$
W = yH_{10}\phi_{16}\phi_{16} + hH_{10}\phi_{16}Y_{16} + \frac{1}{2}MY_{16}Y_{16} + ...
$$
\n•  $y = y_t(t_{GUT}) = y_b(t_{GUT}) = y_\tau(t_{GUT})$ 

- $\phi_1 = N_R$ , Y<sub>1</sub> and Higgs triplets masses  $\sim M_{GUT}$
- only couplings to 3rd generation

### 19.  $Z$  for  $SO(10)$  inspired model

• RGE for  $Z(t)$  with boundary condition  $Z(t_{GUT}) = 1$ 

$$
\frac{d}{dt}Z_{ij}=-\frac{1}{8\pi^2}\left(\frac{1}{2}d_{kl}\lambda^{*}_{ikl}Z^{-1~*}_{km}Z^{-1~*}_{ln}\lambda_{jmn}-2C^{(r)}_{ij}Z_{ij}g^{2}_{r}\right)
$$

 $\bullet$   $SO(10)$  inspired minimal model with superpotential

$$
W = yH_{10}\phi_{16}\phi_{16} + hH_{10}\phi_{16}Y_{16} + MY_{16}Y_{\overline{16}}
$$

$$
Z_{H_u H_u} = 1 + \frac{6}{5} \epsilon [3g_{GUT}^2 - 5(2h^2 - y^2)](t - t_{GUT})
$$
  
+ 
$$
\frac{24}{25} \epsilon^2 [29g_{GUT}^2 + 35(2h^2 + y^2) - 25(2h^4 + 4h^2y^2 + y^4)](t - t_{GUT})^2
$$
  
+...

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## 20.  $t - b - \tau$  unification



 $W = y H_{10} \phi_{16} \phi_{16} + h H_{10} \phi_{16} Y_{16} + M Y_{16} Y_{\overline{16}}, \quad y = 0.7, \, h = 0.4, M = 10^{10} \, {\rm GeV}$ 

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## 21. Phenomenology of SO(10) inspired GUT model

$$
\tan \beta = 35
$$
,  $\xi = 10^5 \,\text{GeV}$ ,  $M = 10^{14} \,\text{GeV}$ 



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# 22. Phenomenology of SO(10) inspired GUT model

scan over parameters

 $8 < t_M < 14, \quad 0.6 < y < 0.9, \quad 0 < h < 1.2$ 

• check low-energy constraints

 $m_{h^0} \approx 125 \,\text{GeV}, \quad M_{\widetilde{g},\widetilde{q}_{1,2}} > 1.8 \,\text{TeV}, \quad \text{UFB/CCB}, \quad a_\mu, \quad \dots$ 

- for moderate tan  $\beta \sim 20$ : no tachyons,  $\tilde{\tau}$  is NLSP, but threshold corrections to  $y_{b,\tau} \sim 200\%$  or more are needed
- to get ~ 20% threshold correction for  $y_b$  one has to fix tan β ~ 45 → tachyonic  $\tilde{\tau}$
- to avoid instabilities of the potential one could extend spectrum or allow additional messenger couplings

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- $\bullet$  messenger couplings  $\lambda$  not only generate soft terms but can also lead to kinetic mixing
- $\bullet$  wave-function renormalization Z is a handy tool to analyze RG flow of Yukawas; this method can be implemented in a similar way at 2-loop level
- **•** phenomenology of the simplest  $SO(10)$  model is spoiled by tachonic  $\tilde{\tau}$  $\rightarrow$  extend spectrum or allow additional couplings

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