High-Scale SUSY and the Higgs from a Stringy Perspective

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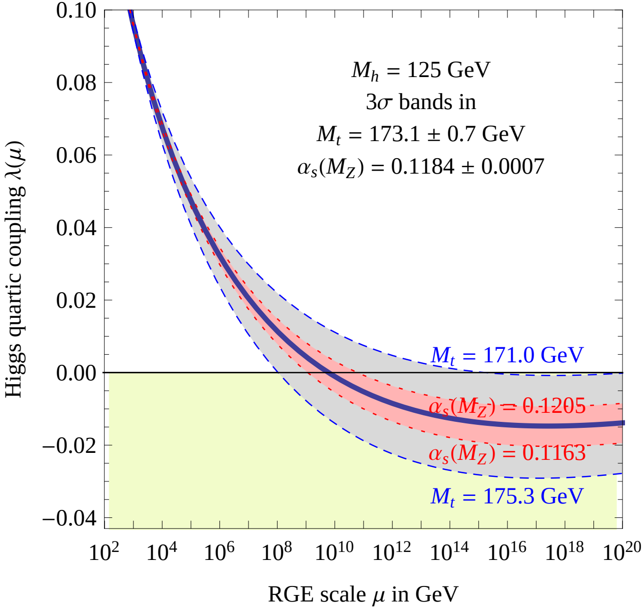
cf. 1204.2551 and 1304.2767 with **A. Knochel and T. Weigand**

Outline

- In the SM, the 'vacuum stabilty scale' μ_λ has emerged as new, important piece of data.
- The vanishing of λ could be related to the breaking approximately shift-symmetric SUSY at that scale.
- This situation arises naturally in the stringy context.
- Alternatively, a SUSY (NMSSM-type) UV completion might appear only far above the scale μ_λ.

NNLO, from Degrassi,.., Espinosa et al., 1205.6497

see also Bezrukov, Kniehl et al. '12; for top-mass precision: Moch et al. '15/'16



Our perspective:

- The critical scale μ_λ could be anywhere between 10^9 and 10^{17} GeV.
- Below μ_λ: just SM.
- The weak scale is fine-tuned;
  The UV completion is stringy;
  SUSY is motivated by the stability of known string models.
- $\lambda = 0$ is the result of a shift-symmetry in the Higgs sector, together with SUSY -breaking at that scale.

The subject has a long history...

- It has always been well-known that, for low m_h, λ runs to zero at some scale $< M_P$ (vacuum stability bound)

Lindner, Sher, Zaglauer '89
Froggatt, Nielsen '96
Gogoladze, Okada, Shafi '07
...
Shaposhnikov, Wetterich 09'
Giudice, Isidori, Strumia, Riotto, ...
Masina '12

- Many attempts were made to turn this into an m_h prediction

- Let us mention two ideas in more detail...

Higgs mass prediction from $\lambda = 0$ at M_P

(Shaposhnikov, Wetterich, 0912.0208)

- One might hope that $\lambda = 0$ emerges in at M_P as a result of quantum gravity
- In 2009, with $m_t \simeq 171$ GeV, this gave a prediction of $m_h = 126$ GeV
- With today's data, this works less well, but is still an option
- The underlying theory assumes a non-perturbative UV fixed point of gravity (asymptotic safety)

Weinberg '79; Reuter '98; Reuter et al. '98...'11

- But it is far from clear why $\lambda = 0$ should come out and who tunes the Higgs mass small....

Higgs mass prediction from $\lambda = 0$ at 'unification scale'

(Gogoladze, Okada, Shafi, 0705.3035 and 0708.2503)

- 5d Gauge-Higgs unification $\rightarrow$ flat Higgs potential
- Based on non-SUSY SM gauge unification (with non-canonical U(1)), one finds a unification scale of 10^{16} GeV
- A prediction of $m_h = 125 \pm 4$ GeV was made
- Obviously, there is strong model dependence in the non-SUSY GUT sector, ... other 'predictions' are possible ....

for another related suggestion see Redi/Strumia '12

String-phenomenologist's perspective

- No strong preference for a particular SUSY breaking scale
- Natural guess: The special scale $\mu(\lambda = 0)$ is the SUSY-breaking scale
- Crucial formula:

$$\lambda(m_s) = \frac{g^2(m_s) + g'^2(m_s)}{8} \cos^2(2\beta)$$

- Reminder:

$$M_H^2 = \begin{pmatrix} |\mu|^2 + m_{H_d}^2 & b \\ b & |\mu|^2 + m_{H_u}^2 \end{pmatrix} = \begin{pmatrix} m_1^2 & m_3^2 \\ m_3^2 & m_2^2 \end{pmatrix}$$

$$\sin(2\beta) = \frac{2m_3^2}{m_1^2 + m_2^2}$$

Need this to be 1!

- Our goal:

  Identify a special structure/symmetry leading to $\tan\beta = 1$ (i.e. to $\lambda = 0$)

- Indeed, such a structure is known in heterotic orbifolds:

  Shift symmetric Kahler potential: $\boxed{K_H \sim |H_u + \overline{H}_d|^2}$

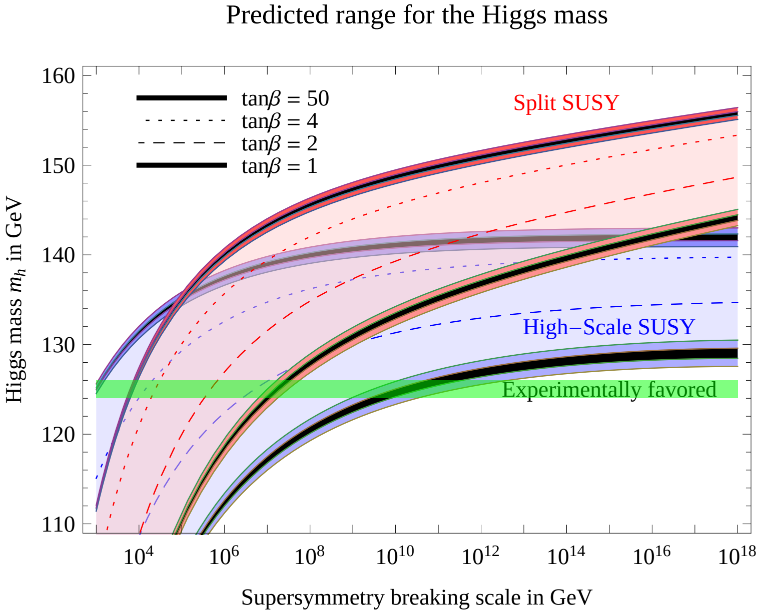
  Lopes-Cardoso, Lüst, Mohaupt '94
  Antoniadis, Gava, Narain, Taylor '94
  Brignole, Ibanez, Munoz, Scheich, '95...'97

- Note: The actual shift symmetry transformation is

$$H_u \to H_u + \alpha \; , \qquad H_d \to H_d - \overline{\alpha} \, .$$

  This guarantees a light doublet, even after SUSY breaking.

NNLO, from Degrassi,.., Espinosa et al., 1205.6497



In more detail:

$$K_H = f(S,\overline{S})|H_u + \overline{H}_d|^2$$

Assuming $F_S \neq 0$ and $m_{3/2} \neq 0$ this gives

$$m_1^2 = m_2^2 = m_3^2 \quad = \quad \left| m_{3/2} - \overline{F}^S f_{\overline{S}} \right|^2 + m_{3/2}^2 - F^S \overline{F}^S (\ln f)_{S\overline{S}}$$

- One of the concrete modern realizations is through F-theory GUTs, with a D7-brane 'bulk Higgs' à la

Donagi, Wijnholt, '11

- In this setting one expects $F^S = 0$ and hence

$$m_i^2 = 2m_{3/2}^2 \,.$$

- To understand the physical origin of the shift symmetry, the simplest context is that of orbifold GUTs

K. Choi et al. '03
AH, March-Russell, Ziegler '08
Brümmer et al. '09...'10
Lee, Raby, Ratz, Ross, ... '11

- Indeed, one has the 5d breaking pattern

$$\mathrm{SU}(6) \to \mathrm{SU}(5)\times\mathrm{U}(1)\,; \quad 35 = 24+5+\overline{5}+1\,.$$

- The Higgs arises from the scalar and vector of the 5d multiplet

$$\mathrm{Higgs}_{\,5,\overline{5}} = \Sigma + iA_5$$

(the shift symmetry comes from 5d gauge trfs., $A_5 \to A_5 + c$).

cf. Gogoladze, Okada, Shafi '07

- This also happens in full-fledged 10d heterotic string constructions, but it is much more generic:

  heterotic WLs $\leftrightarrow$ type IIA / D6-WLs $\leftrightarrow$ type IIB / D7-WLs
  or positions

- These and other origins of the Higgs-shift-symmetry and of $\tan\beta = 1$ have also been explored in

  Ibanez, Marchesano, Regalado, Valenzuela '12
  Ibanez, Valenzuela '13

- In particular, they observe that to get $\tan\beta = 1$, a $\mathbb{Z}_2$ exchange symmetry acting on H_u, H_d is sufficient; the rest is done by the usual tuning...

$$M_H^2 = \begin{pmatrix} m_1^2 & m_3^2 \\ m_3^2 & m_2^2 \end{pmatrix}$$

Comments

- Clearly, we eventually need more phenomenological implications of 'stringy high-scale SUSY' (e.g. in cosmology)

- For example, axion(s), cosmological moduli and a possible 'dark radiation sector' can be potentially related to the high SUSY-breaking scale

  Chatzistavrakidis, Erfani, Nilles, Zavala '1206...
  Higaki, Hamada, Takahashi '1206...
  Cicoli, Conlon, Quevedo,... Angus,... '12...'13

- The situation concerning non-SUSY F-theory unification in this context is interesting but complicated....

  Ibanez et at. '12
  AH, Unwin, '14

Returning to our shift-symmetry proposal we now ask about

Corrections? Precision?

- The superpotential (e.g. top Yukawa) breaks the shift symmetry

- The crucial point is compactification

  Shift symmetry is exact (gauge symmetry!) in 10d.
  The shift corresponds to switching on a WL.
  This is not a symmetry in 4d (4d-zero modes 'feel' the WL).
  4d-loops destroy the shift symmetry of Kähler potential.

- Optimistic approach to estimating the 'goodness' of our symmetry:

  Symmetry-violating running between m_c and m_S
  $\Rightarrow$ Correction $\delta \sim \ln(m_c/m_S)$

More explicitly:

$$M_H^2 = (|\mu|^2 + m_H^2) \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} + \begin{pmatrix} \delta|\mu|^2 + \delta m_{H_d}^2 & \delta b \\ \delta b & \delta|\mu|^2 + \delta m_{H_u}^2 \end{pmatrix}$$

$$= \quad \text{symmetric} \quad + \quad \text{loop violation}$$

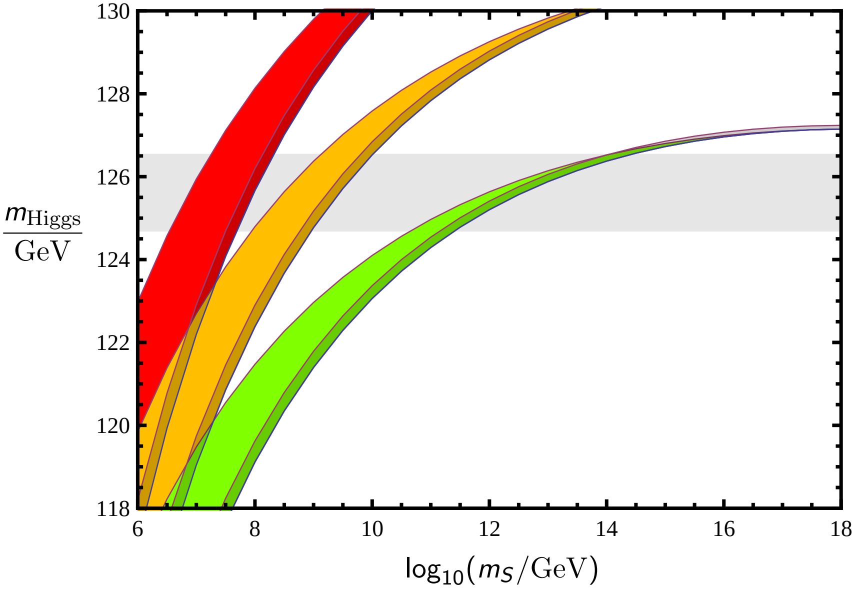
- Leading effects: y_t and gauge

$$\delta M_H^2 = f(\epsilon_y, \epsilon_g, m_{\rm soft}) \qquad ; \qquad \epsilon_y = \int_{\ln m_s}^{\ln m_c} dt \, \frac{6|y_t|^2}{16\pi^2}$$

- Enforce det $M_H^2 = 0$ after corrections $\Rightarrow$ $\epsilon_y, \epsilon_g, m_{\rm soft}$ are related

$$\cos 2\beta = \epsilon_y \times \{\text{calculable } \mathcal{O}(1) \text{ factor}\}$$

Assumption: $m_S < m_c < 100 m_S$ and $m_S < m_c < \sqrt{m_S M_P}$



Another type of corrections:

$$\delta\lambda_{TH}(m_S) = \frac{3y_t^4}{16\pi^2}\Big[\frac{X_t^2}{m_S^2}\Big(1 - \frac{X_t^2}{12m_S^2}\Big) + 2\log\big(\frac{m_{\tilde{t}}}{m_S}\big)\Big]$$

with

$$X_t = A_t - \mu\cot\beta \approx A_t - \mu$$

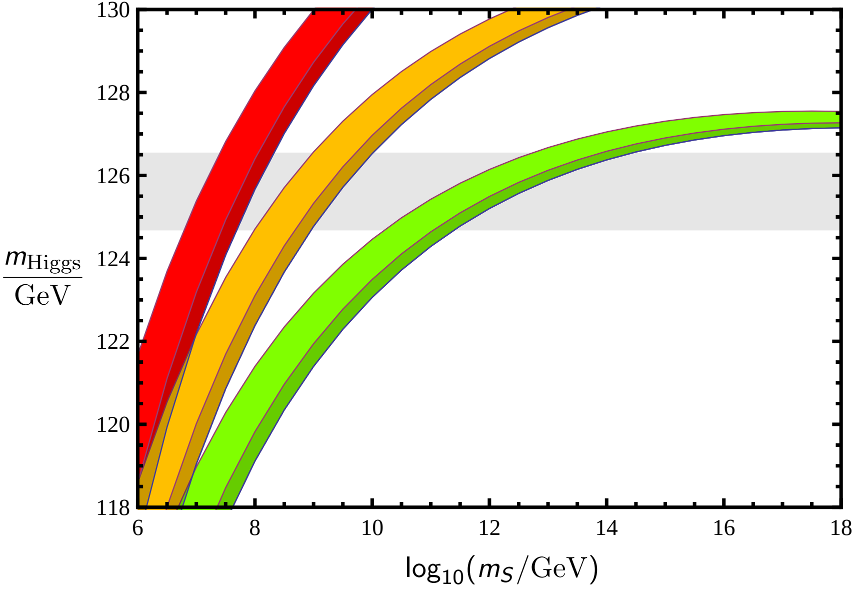
- For $X_t^2 = 0 \ldots 6m_S^2$, they are in the range

$$\delta\lambda_{TH}(m_S) = 0 \ldots 3 \times \frac{3y_t^4}{16\pi^2}$$

- These are qualitatively different from SUSY thresholds and should hence presumably not be absorbed in an 'effective SUSY breaking scale'

Drees, priv. comm.

A-term corrections for $X_t^2 = m_S^2$ and $X_t^2 = 6m_S^2$



From unstable high-scale to metastable low-scale theories:

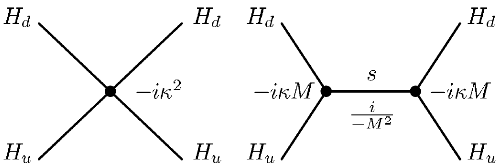
- So far, we argued that
  SUSY should appear at least at the scale μ_λ.

- However, this can avoided with very little extra effort:

- Let string theory produce a high-scale NMSSM, with a large supersymmetric mass M for the singlet S,

$$W = \kappa S H_u H_d + \frac{1}{2} M S^2 \,.$$

- Clearly, integrating out S will not induce a quartic coupling due to a supersymmetric cancellation...



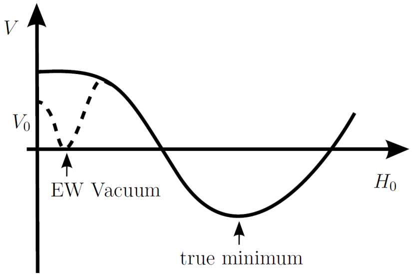
- However, adding additionally a negative soft mass-squared upsets this cancellation and gives a negative quartic effect:

Giudice/Strumia '11

$$V_{\Lambda=M} \quad \supset \quad \kappa^2 \frac{m_s 2}{M^2 + m_s^2} \, |H_u H_d|^2 \, .$$

- We propose to make this effect large enough to produce a non-negligible $\lambda < 0$ at the scale m_s.
- We also still have a shift-symmetric Kahler potential and hence $\tan\beta = 1$ at LO.

- Our theory is now weakly unstable at the SUSY breaking scale.
- This is cured in the UV→IR RGE-running:



- 'Our' minimum is generated only radiatively, as λ runs from negative to positive values in a loop-calculation based on an unstable vacuum.
- Thus, we have a simple UV completion of the meta-stable SM.

- This setting is reminicsent of situations with tachyonic high-scale soft masses

see e.g.
Dermisek/Kim '06
Ellis/Lebedev/Olive/Srednicki '08

- It is interesting to work out the cosmology of this setting in more detail...

Abel/Chu/Jaeckel/Khoze '06
Lebedev/Westphal '12

see also recent work by
Enqvist, Lebedev, Karciauskas, Rusak, Zatta, Gross, ...
Espinosa et al.

Conclusions / Summary

- It is conceivable that we have to expect new physics not at a TeV, but only at the 'vacuum stability scale' μ_λ.

- Well-motivated guess: SUSY broken with $\tan\beta = 1$ at μ_λ

- Possible structural reason: shift symmetry in Higgs sector

  (Predictivity, i.e. m_h , m_t , $\alpha_s \Rightarrow m_s$ remains strong, even if shift symmetry is only approximate)

- But: SUSY breaking above μ_λ with $\lambda < 0$ is also possible

- This is a very natural UV-completion for the minimalist 'metastability scenario' without new physics near μ_λ.