The Higgs mass from a String-Theoretic Perspective

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

Outline

- We could be stuck with just the SM at low energies
- m_h (or λ) has emerged as a new piece of data constraining high-scale physics
- Interesting fact: λ runs to zero below or near M_P
- What happens at this distinguished energy scale?
- Main idea: high-scale SUSY with $\lambda = 0$ after SUSY-breaking

Outline - continued

- The weak scale is fine-tuned;
  the motivation of SUSY is hence string-theoretic

- $\lambda = 0$ is the result of a (stringy) shift-symmetry

  AH, Knochel, Weigand '12

  or an (equally stringy) Z_2 exchange symmetry

  Ibanez, Marchesano, Regalado, Valenzuela '12

- We want to study the geometric details of these mechanisms

- Closely related: The very same shift-symmetry may be reponsible for a flat potential in fluxbrane inflation

AH, Kraus, Küntzler, Lüst, Steinfurt, Weigand, Westphal '11-12
Sebastian Kraus – parallel talk

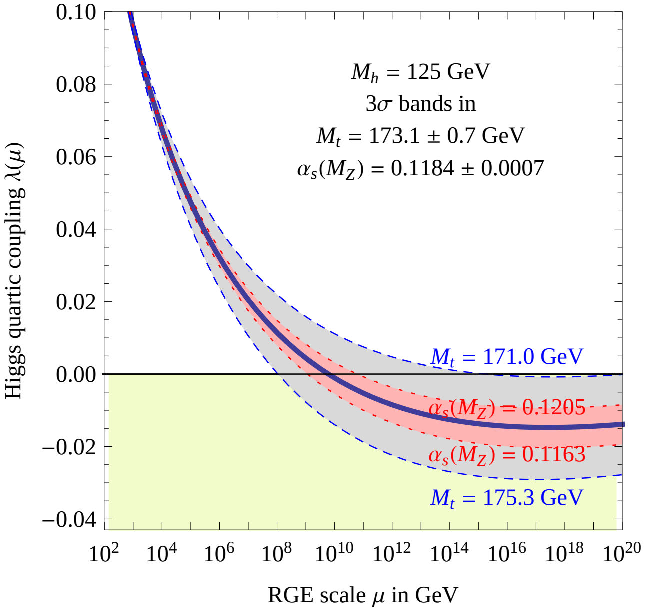
The subject has a long history...

- Well-known: 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

- It has been attempted to turn this into an m_h prediction

Degrassi/Elias-Miro/Espinosa/Giudice/Isidori/Strumia, 1205.6497



Phenomenological preliminaries

- Of course, high-scale SUSY has been considered before

  Giudice, Romanino '04
  Arkani-Hamed, Dimopoulos, Arvatinaki, Kaplan,.. '04..'12
  Hall, Nomura '09

- Quartic coupling λ at SUSY-breaking scale m_s:

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

- Reminder:

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

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

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 symmetry: $\boxed{K_H \sim |H_u + \overline{H}_d|^2}$

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

- The physical origin is most easily seen in '5d orbifold GUT language':

5d SU(6) $\to$ SU(5)$\times$U(1) ; $35 = 24 + 5 + \bar{5} + 1$; Higgs$= \Sigma + iA_5$

Choi, Haba, Jeong et al. '03; AH, March-Russell, Ziegler '08
Brümmer et al. '09...'10; Ben-Dayan, Einhorn '10; Lee, Raby, Ratz, Ross, '11

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

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

$$\Rightarrow \quad M_H^2 \sim \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \quad \Rightarrow \quad \tan\beta = 1$$

Note:

- Combined with the $\det(M_H^2) = 0$ condition, a $\mathbb{Z}_2$ exchange symmetry on H_u, H_d is actually sufficient:

$$M_H^2 = \begin{pmatrix} m_1^2 & m_3^2 \\ m_3^2 & m_2^2 \end{pmatrix} \quad \Rightarrow \quad M_H^2 \sim \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

Ibanez, Marchesano, Regalado, Valenzuela '12

Predictivity/Applications

- Clearly, we eventually need more phenomenological implications of 'stringy high-scale SUSY'

- Among others, axion(s), cosmological moduli, gauge unification and proton decay can be potentially related to the high SUSY-breaking scale

  Chatzistavrakidis, Erfani, Nilles, Zavala '12
  Anchordoqui, ..., Vlcek '12
  Ibanez, Marchesano, Regalado, Valenzuela '12
  Ibanez, Valenzuela '13

- Particularly interesting point: The term $H_u H_d \subset K$, which is potentially controlled by the shift symmetry, is crucial for reheating and and hence dark radiaton abundance

  Higaki, Kamada, Takahashi '12
  Cicoli, Conlon, Quevedo,... Angus,... '12...'13

...let's turn to theory

Wilson lines on D7 branes

- Recall structure of IIB Kähler potential

$$K \supset -3\ln(T + \overline{T} - a\overline{a} + \ldots)$$

Jockers, Louis, '04

(T – Kähler and C_4; a – two Wilson lines A_1, A_1')

- Can we hope that $a\overline{a} \subset (a + \overline{a})^2$? No, because of CS-term:

$$\int_{D7} C_4 \wedge dA_1 \wedge dA_1 = \int_{D7} A_1 \wedge dC_4 \wedge dA_1$$

...which in general destroys the shift symmetry.

however:

Wilson lines on D6 branes

- Recall structure of IIA Kähler potential

$$K \supset -\ln(-i(S-\overline{S}) - u\overline{u} + \ldots)$$

Kerstan/Weigand, Grimm/Lopes '11

(S – dilaton, volume and C_3; $\quad u = \Phi + iA_1$ – brane position and Wilson line)

- Here, the CS-term allows for $u\overline{u} \subset (u+\overline{u})^2$:

$$\int_{D6} C_3 \wedge dA_1 \wedge dA_1 = \int_{D6} A_1 \wedge dC_3 \wedge dA_1$$

(to get kinetic mixing, one would need $dC_3 \sim$ (4d 3-form) $\times$ (CY 1-form) - the latter is not available) finally and most importantly:

D7-brane position moduli

- Recall structure of IIB Kähler potential

$$K \supset -\ln(-i(S-\overline{S}) - \zeta\overline{\zeta} + \ldots)$$

Jockers/Louis '04

(S – dilaton and C_0; ζ – two brane position moduli)

- Mirror symmetry: $u \leftrightarrow \zeta$

- Thus, at large complex structure, we expect:

$$K \supset -\ln[-i(S-\overline{S}) - k_{D7}(z,\overline{z},\zeta-\overline{\zeta})]$$

Note: Re(ζ) corresponds to the D7 position along the T^3 of the Strominger-Yau-Zaslov picture of mirror symmetry

ζ corresponds to a

Bulk Higgs

in the context of type IIB/F-theory GUTs (e.g. $SU(6) \to SU(5)$)

Donagi, Wijnholt, '11

- Assuming that S and all z's are stabilized supersymmetrically, the 'Giudice-Masiero' contribution to the Higgs mass matrix is suppressed
- The physical soft Higgs masses then read

$$\boxed{m_1^2 = m_2^2 = m_3^3 = 2m_{3/2}^2}$$

(This is our main 'success story')

Intersection-curve Higgs

- In the majority of type IIB/F-theory models, the Higgs comes from intersection curves
- We need to understand transition from

$$K \supset \frac{1}{s}|H_u + \overline{H}_d|^2$$

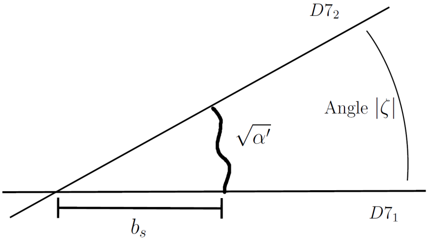
to

$$K \;\supset\; f_1(s, T, \overline{T})|H_d|^2 + f_2(s, T, \overline{T})|H_u|^2 + f_3(s, T, \overline{T}) H_u H_d + \text{h.c.}$$

- This is realized in a continuous localization process, which we understand at least parametrically:

From the bulk to the intersection-curve Higgs

Conlon/Cremades/Quevedo '06, Aparicio/Cerdeno/Ibanez '08, Dudas/Palti '09,...



- The key is the size b_s of the region where the Higgs localizes. After some algebra one finds:

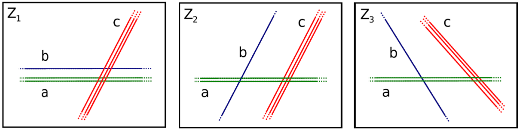
$$K \sim \frac{1}{s + |\zeta|^2 \sqrt{ts}} |H_u|^2 + \cdots$$

- Unfortunately, the coefficient of $H_u H_d$ remains a challenge for the future...

A $\mathbb{Z}_2$-symmetry from intersecting D6-branes?

Ibanez, Marchesano, Regalado, Valenzuela '12

- The two Higgs doublets come from a 5d hypermultiplet on the (non-generic) intersection curve of two D6-branes



- The crucial $B\mu$ term comes from one of the three D-terms of the local $\mathcal{N} = 2$ theory
- In 4d $\mathcal{N} = 1$ language, the relevant term must be an F-term
- Thus, one needs F-term breaking from brane angles, which requires a 'non-factorizable' brane geometry.
- While this can in principle be achieved on tori, the situation in generic CY geometry remains unclear

...in more detail...

- The usual, $\mathcal{N}=1$ D-term:

$$\mathcal{L} \supset g^2 \left(\xi + |H_u|^2 - |H_d|^2\right)^2$$

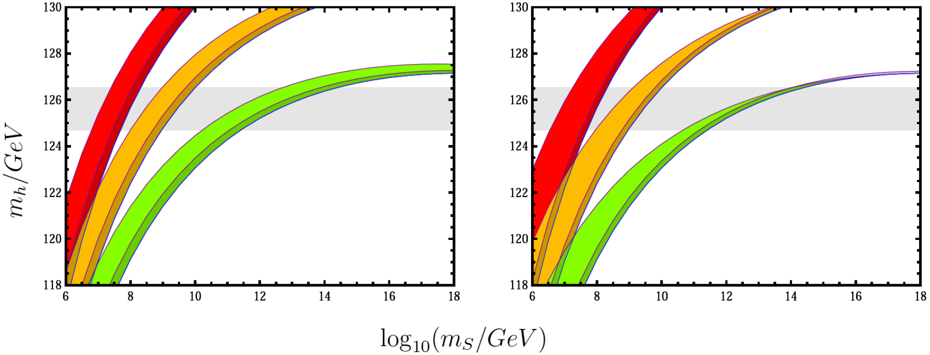
- The $\mathcal{N}=2$ D-term, which corresponds to an $\mathcal{N}=1$ F-term of the'surviving' SUSY

$$\mathcal{L} \;\supset\; g^2 \left(\xi + |H_u - H_d^\dagger|^2 - |H_d^\dagger + H_u|^2\right)^2 \;\supset\; -4g^2 \xi H_u H_d + \text{h.c.}$$

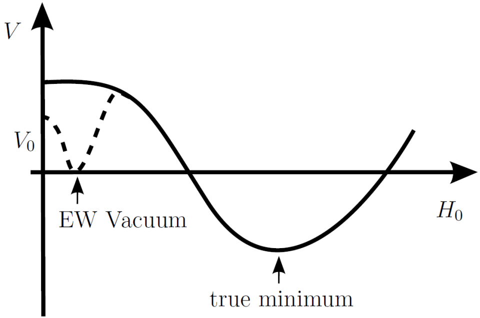
Corrections? Precision?

cf. parallel talk of A. Knochel + our last paper

- The phenomenological meat is in the correlation between SUSY breaking scale m_S and m_h (given $\tan\beta = 1$ at m_S)
- The two main theoretical errors come from SUSY running and loops at m_S



- Amusingly, SUSY can be broken even far above the scale where $\lambda = 0$
- One needs to enforce $\tan\beta = 1$ by shift symmetry and correct λ by an NMSSM-like scalar, giving $\lambda < 0$ at m_S



- 'Our' minimum is generated only radiatively
- This can be viewed as a microscopic realization of the metastability scenario

Conclusions / Summary

- In the absence of new electroweak physics at a TeV, the 'vacuum stability scale' μ_λ may be a hint at new physics
- Well-motivated guess: SUSY broken with $\tan\beta = 1$ at μ_λ
- Possible structural reason: shift symmetry in Higgs sector
- A bulk Higgs in type IIB/F-theory GUTs at large complex structure works best (so far...)
- Intersection-curve Higgs, D6-brane Higgs with $\mathbb{Z}_2$ symmetry and Higgs in fractional-D3 models require more work
- But: SUSY breaking above μ_λ with $\lambda < 0$ is also possible; cosmological challenges need further study

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