Shift and $\mathbb{Z}_2$ symmetries in the Higgs sector

Arthur Hebecker (Heidelberg)

Outline

- Interesting fact:
  The quartic coupling λ runs to zero below or near M_P
- This talk: high-scale SUSY with $\lambda = 0$ after SUSY-breaking
- 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/'13

  or an (equally stringy) $\mathbb{Z}_2$ exchange symmetry

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

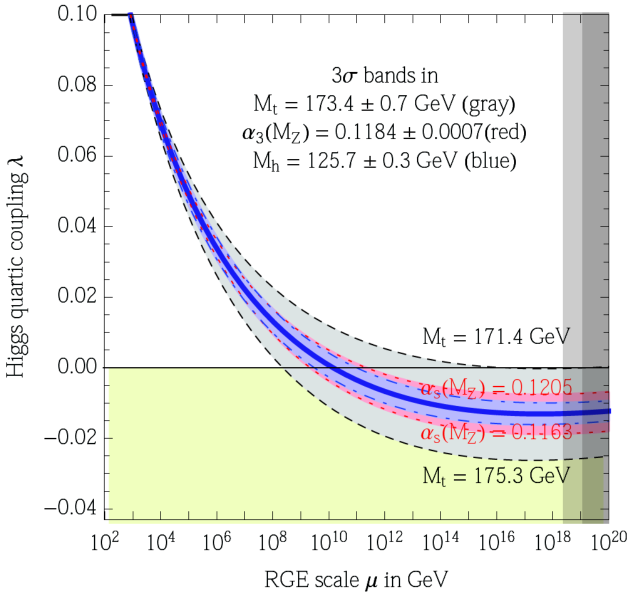
The subject has a long history...

- 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, ...
  Redi, Strumia '12
  Masina '12

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

Buttazzo et al. 1307.3536



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:

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

- β is the rotation angle needed to diagonalize

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

- Our goal is a symmetry leading to

$$M_H^2 \sim \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

- 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

- It can be traced to the Higgs being a Wilson-line of a higher-dimensional SYM theory

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, the Kähler potential

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

gives

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

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

Note:

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

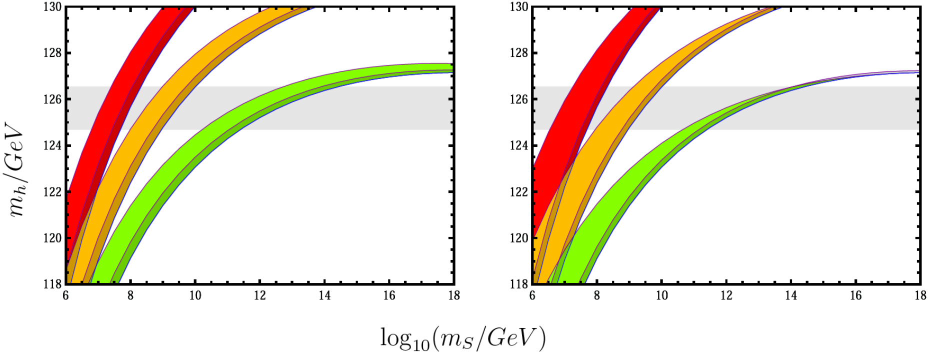
$$M_H^2 = \begin{pmatrix} m_1^2 & m_3^2 \\ m_3^2 & m_2^2 \end{pmatrix} \qquad \Rightarrow \qquad M_H^2 \sim \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

Ibanez, Marchesano, Regalado, Valenzuela '12

Corrections? Precision?

- 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



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, Antoniadis, ..., 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

Our theory-focus is a (Higgs) shift symmetry in D-brane models

- Recall structure of IIB Kähler potential for D7 Wilson lines a:

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

Jockers, Louis, '04

Note: Due to Chern-Simons term, $a\bar{a} \not\subset (a + \bar{a})^2$

- By contrast, for D6 Wilson lines u in type IIA one has:

$$K \supset -\ln(-i(S - \overline{S}) - (u + \overline{u})^2 + \ldots)$$

Kerstan/Weigand, Grimm/Lopes '11

- By mirror symmetry, for D7 brane positions ζ one has:

$$K \supset -\ln(-i(S - \overline{S}) - (\zeta + \overline{\zeta})^2 + \ldots)$$

ζ corresponds to a

Bulk Higgs

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

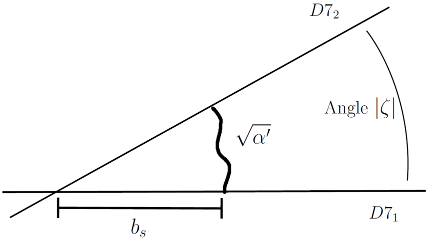
- The physical soft Higgs masses then read

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

(This is our main 'success story')

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:

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

- 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 $\mathbb{Z}_2$-symmetry is automatic if $m_{H_u}^2 = m_{H_d}^2 = 0$ (i.e., just μ and $B\mu$ term are present).

- Can this be realized using SUSY breaking (i.e. D-terms) from branes at angles?

- Apperently no, since the usual D-term potential

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

gives $B\mu = 0$ and $m_{H_u}^2 = -m_{H_d}^2 \neq 0$.

- However, a field-redefinition $\{H_u, H_d^\dagger\} \rightarrow \{(H_u - H_d^\dagger), (H_d^\dagger + H_u)\}$ may help.

A $\mathbb{Z}_2$-symmetry from D6-branes (continued)

- Indeed:

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

while

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

- However, this field redefinition corresponds to an $SU(2)_R$ rotation of $\mathcal{N} = 2$ supersymmetry

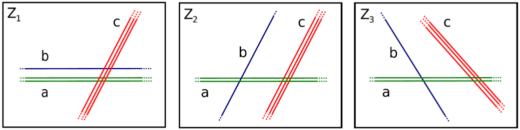
- Hence, there is a clash with the $\mathcal{N} = 1$ supersymmetry used when calculating the MSSM scalar potential

  [Note: We can not simply break $\mathcal{N} = 2 \to \mathcal{N} = 0$ since the corresponding scalar potential has no flat direction]

A $\mathbb{Z}_2$-symmetry from intersecting D6-branes (continued)

- The idea might nevertheless work as follows:

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

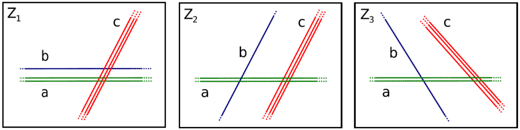


- While $SU(2)_a$ and $SU(3)_c$ are the usual Standard Model groups, $U(1)_b$ is not the hypercharge

- $B\mu$ comes from one of the 'three D-terms' of the local $\mathcal{N} = 2$ theory associated with $U(1)_b$ and the Higgs doublets

- In 4d $\mathcal{N} = 1$ language, the relevant term must be an F-term

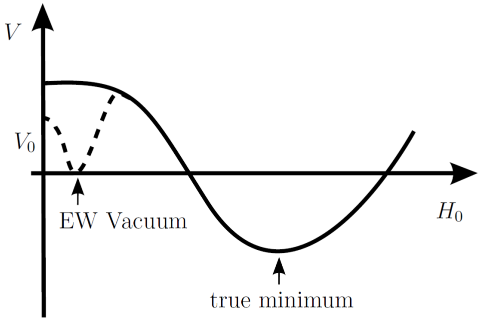
A $\mathbb{Z}_2$-symmetry from intersecting D6-branes (continued)



- Thus, one needs F-term breaking from brane angles, which requires a 'non-factorizable' brane geometry.
- We explicitly give the required rotation of the $U(1)_b$ brane
- As a non-trivial extra condition, the $U(1)_b$ gauge coupling needs to be small to suppress its D-term potential
- While this (may) in principle work on tori, the analysis in generic CY geometry requires more effort

- Amusingly, SUSY can be broken even far above the scale where $\lambda = 0$
- One needs to enforce $\lambda = 0$ 'from the Kähler potential' and correct it by an NMSSM-like scalar, giving $\lambda < 0$ at m_S

Giudice, Strumia '11



- '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 reason: Shift or $\mathbb{Z}_2$ symmetry in Higgs sector
- Specific settings include: Bulk Higgs in type IIB/F-theory GUTs, Intersection-curve Higgs, D6-brane Higgs (with $\mathbb{Z}_2$ symmetry), Higgs in fractional-D3 models, ...
- 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