Relating the Measured Higgs Mass to High-Scale Physics

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Outline

- Taking the data at face value, we could be stuck with just the standard model at low energies
- The Higgs mass value has emerged as a new piece of data constraining high-scale physics
- The crucial hint is that the quartic coupling λ runs to zero below or near the Planck scale
- What happens at this distinguished energy scale?
- In addition to the review part, I will focus on 1204.2551 with **A. Knochel and T. Weigand**

  (plus ongoing work with **Goodsell, Knochel and Weigand**)

Outline - continued

- The main idea here is that the 126-GeV-Higgs may be pointing to 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 shift-symmetry
- Closely related: The very same symmetry may be reponsible for a flat potential in fluxbrane inflation

More detailed motivation:

- We have a Higgs at 126 GeV and nothing else (yet?)

  Of course: low-scale SUSY is still OK
  Also: Muon-$(g-2)$; $h \to \gamma\gamma$ excess; 130-GeV γ-ray line...

- Nevertheless: What if we just had to accept the fine-tuned non-SUSY SM for a large energy range?

- Well-known: for low m_h, λ runs to zero at some scale $< M_P$ (vacuum stability bound)

  Lindner, Sher, Zaglauer '89
  Gogoladze, Okada, Shafi '07
  ...
  Shaposhnikov, Wetterich 09'
  Giudice, Isidori, Strumia, Riotto, ...

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

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, so that other 'predictions' were also discussed in these papers

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

(Shaposhnikov, Wetterich, 0912.0208)

- Let us assume that gravity is UV-safe, i.e., there exists a non-perturbative UV fixpoint of 4d quantum gravity

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

- Then it may be natural to assume that $\lambda = 0$ emerges in the IR (i.e. at M_P) as a result of this strong dynamics

- In 2009, with $m_t \simeq 171$ GeV, this gave a prediction of $m_h = 126$

- The details are, however, more complicated:

- Since there is (presumably) no 'landscape' in this approach, the smallness of μ in $-\mu\varphi^2 + \lambda\varphi^4$ requires explanation

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

- A possible scenario is that, in the UV regime above M_P, the $-\mu\varphi^2$ operator is irrelevant

Wetterich, 1112.2910

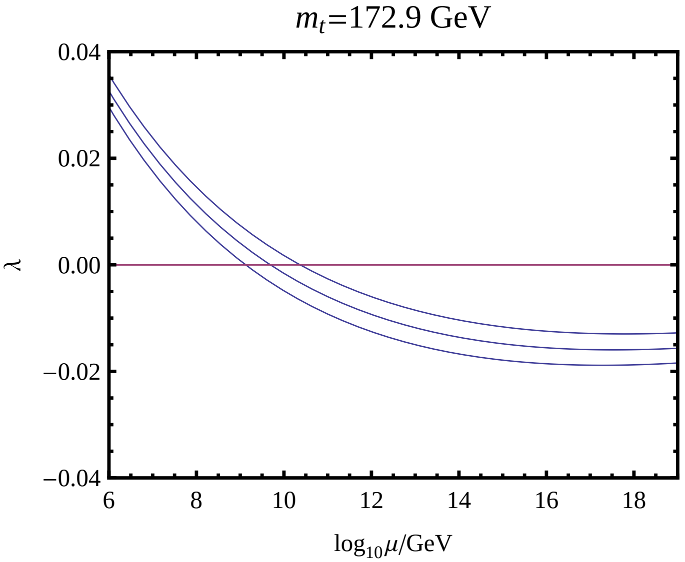
- It is hence driven to zero with high precision (like the curvature term during inflation)

- In the same regime, the Einstein-Hilber term is relevant and comes to dominate at M_P

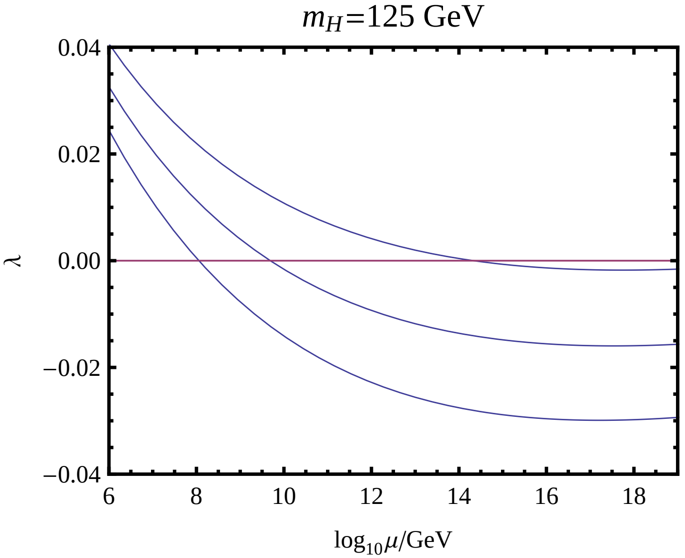
- Then the evolution in the low-energy domain below M_P starts with $\lambda = 0$ and m_h tiny, thereby explaining the electroweak hierarchy

- In my opinion, the technical realization of this scenario, including the parametric control of the UV-fixpoint calculations are imortant open issues...

Running of λ (for a ± 1 GeV variation of m_{Higgs})

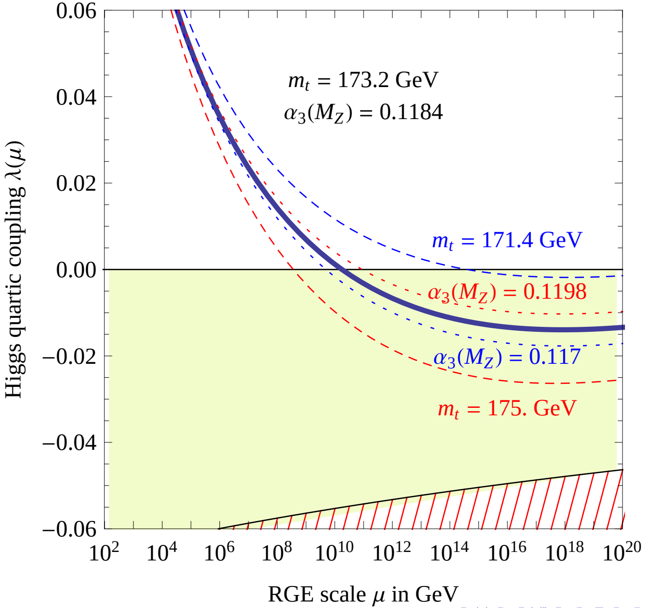


Running of λ (for a 2-σ variation of $m_{\rm top}$)



From Elias-Miro/Espinosa/Giudice/Isidori/Riotto/Strumia, 1112.3022

$m_h = 126$ GeV



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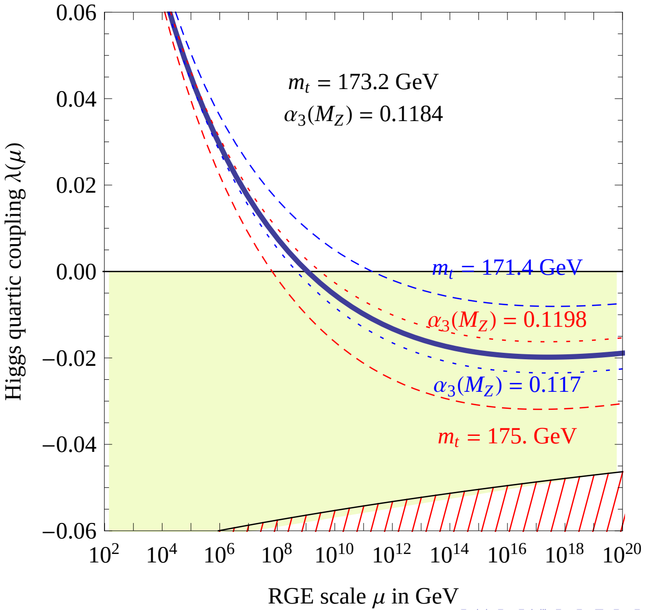
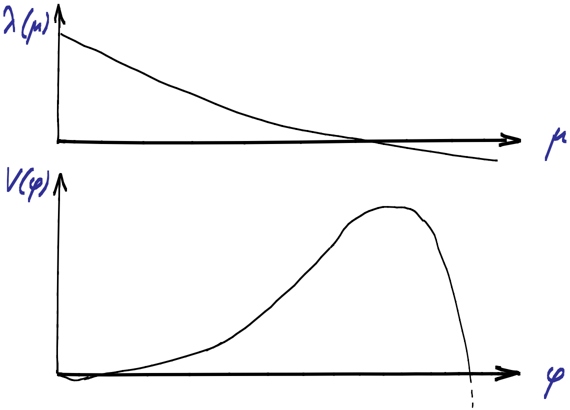
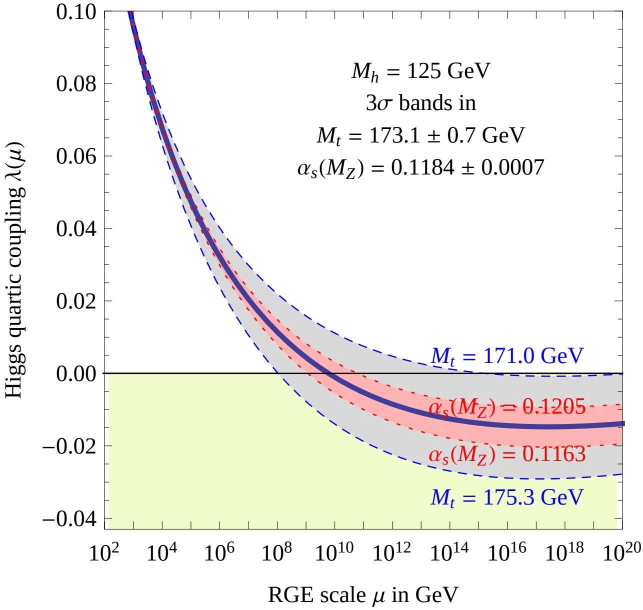


(very!) schematic picture of running λ and of V



NNLO, from Degrassi et al., 1205.6497



String-phenomenologist's perspective

- Insist on stringy UV completion (for conceptual reasons)
- Expect SUSY at string/compactification scale (stability!)
- 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!

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

  Arkani-Hamed, Dimopoulos '04
  Giudice, Romanino '04
  ...

- Also, relations $\tan\beta \leftrightarrow \lambda(m_s) \leftrightarrow m_h$ have been discussed

  cf. the 140-GeV-Higgs-mass-prediction of Hall/Nomura, '09

- Our goal:

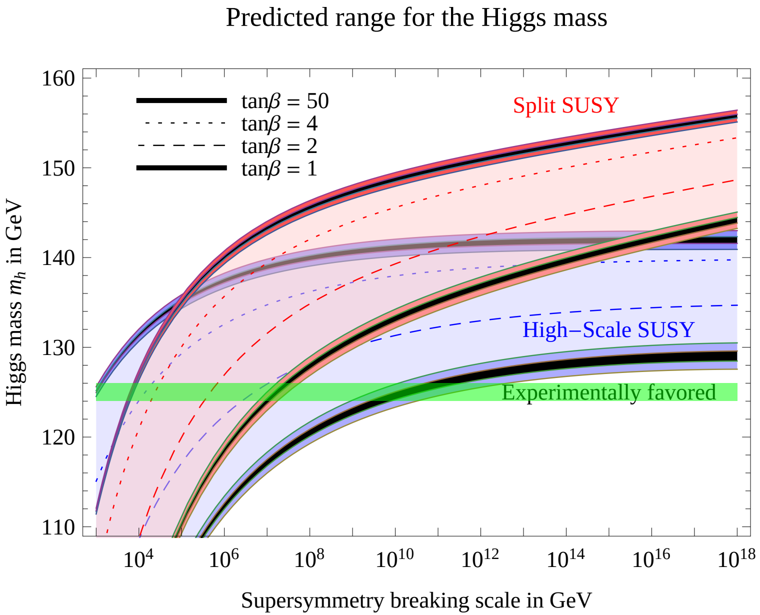
  Identify a special structure/symmetry leading to $\tan\beta = 1$ (i.e. to $\lambda = 0$)

- 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

NNLO, from Degrassi 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

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

- This shift-symmetric Higgs-Kähler potential has also been rediscovered/reused in orbifold GUTs

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

- In this language, it is easy to see the physical origin:

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

cf. Gogoladze, Okada, Shafi '07

Comments

- This simple understanding of the shift-symmetry lets us hope that it is 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 recently also been explored in

  Ibanez, Marchesano, Regalado, Valenzuela '1206...

- In particular, they observe that to get $\tan\beta = 1$, a 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 - continued

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

- A natural setting for more conrete model building on the type IIB side is the LARGE volume paradigm

  Balasubramanian, Berglund, Conlon, Quevedo, '05

- In particular, 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 '1208...

- For example, the axion scale can be fixed by also appealing to a 'remote-SUSY' unification model (Ibanez et al.)

Comments - continued

- The '$\lambda = 0$ scale' might associated be with the axion scale, also without SUSY (but possibly with strong dynamics)

  Giudice, Rattazzi, Strumia, '1204...
  Redi, Strumia, '1204...
  Hertzberg, '1210...

- In an alternative line of thinking, one can try to avoid the high-scale instability of the SM by adding new scalars and/or U(1)s at lower energies

  Anchordoqui, Antoniadis, Goldberg, Huang, Lüst, Taylor, Vlcek '1208...

- A stabilization effect can also arise from the thresholds of a heavy scalar

  Elias-Miro, Espinosa, Giudice, Lee, Strumia '1203...'

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:

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

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

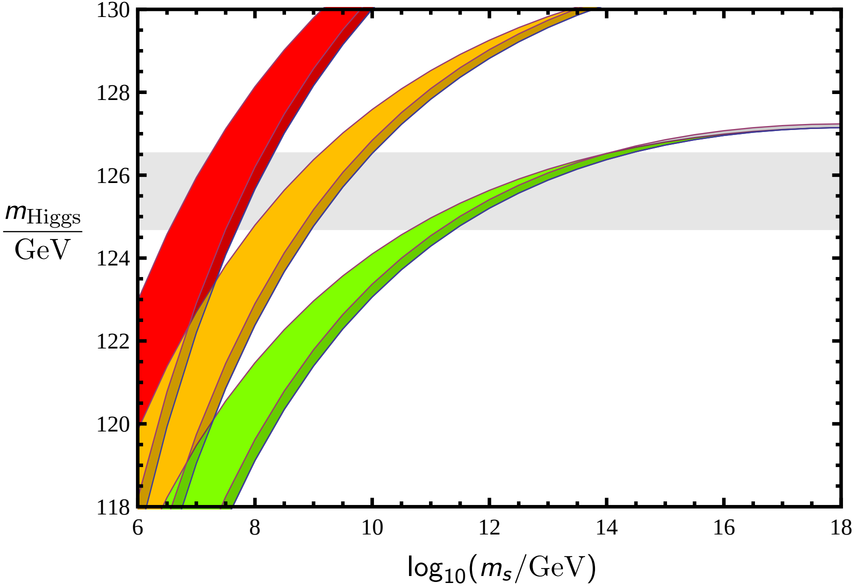
- Leading effects: y_t and gauge

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

- 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:

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

with

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

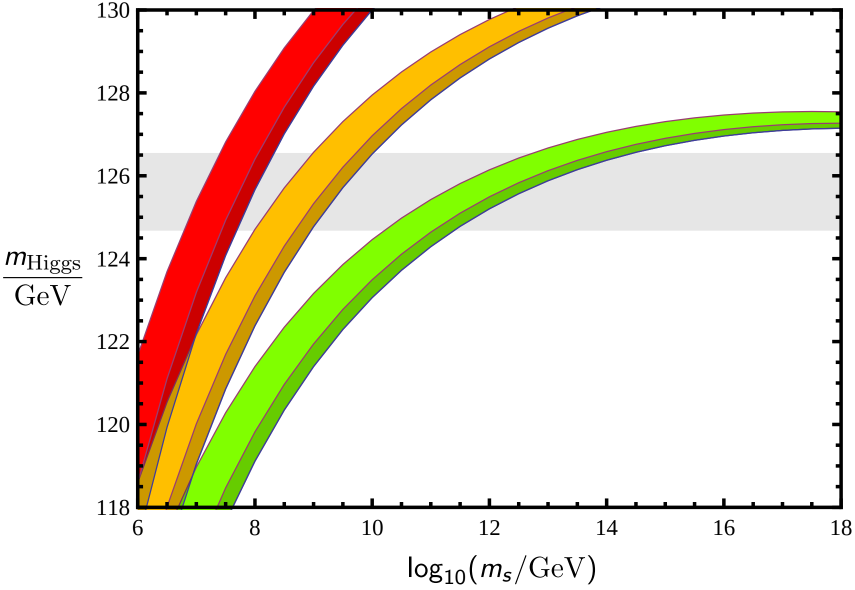
- For $X_t^2 = 0\ldots 6m_S^2$, they are in the range

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

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

Drees, priv. comm.

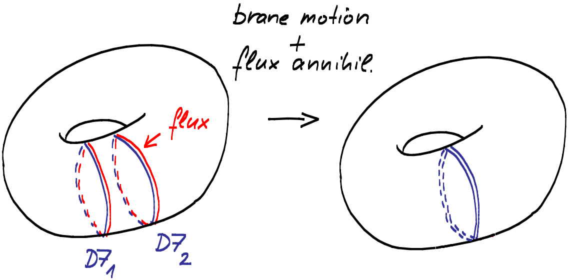
A-term corrections for $X_t^2 = m_S^2$ and $X_t^2 = 6m_S^2$



A different application of the same shift symmetry

AH, Kraus, Lüst, Steinfurt, Weigand, 1104.5016
. . . , Küntzler, 1207.2766
. . . , Arends, Heimpel, Mayrhofer, Schick, 12...

- Fluxbrane inflation with flat direction protected by shift symmetry for D7-brane motion



- Related to WLs by mirror symmetry / T-duality

Fluxbrane inflation

- Crucial fact: At large volume (i.e. weak flux F), the potential is much more flat than in brane-antibrane inflation:

$$V \sim 1 - \frac{g_s}{r^{d_\perp - 2}} \quad \rightarrow \quad V \sim F^2 - F^4 \frac{g_s}{r^{d_\perp - 2}}$$

Hence: $\eta \sim F^2 \ll 1$

- Note: This is conceptually similar to D3/D7 inflation

Dasgupta, Herdeiro, Hirano, Kallosh, '02

and T-dual to inflation from branes at angles and Wilson lines

Garcia-Bellido, Rabadan, Zamora, '01
Avgoustidis, Cremades, Quevedo, '06

Flat direction / shift symmetry

- Chose brane/bulk fluxes such that W_0 does not depend on φ.
- Of course, since $W_0 \not\equiv 0$, the usual 'η-problem of supergravity' is still present:

$$K = -\ln(S + \overline{S} + \kappa(\varphi, \overline{\varphi})) + \cdots \qquad \Longrightarrow \qquad \eta \simeq 1 \text{ from } V_F$$

[Here κ is the Kähler potential on the D7-brane moduli space; similar to situation in KKLMMT.]

- Fact: F-theory on K3×K3 has $\kappa = \kappa(\varphi + \overline{\varphi})$
- We expect this shift-symmetric structure to arise more generally in the large complex structure limit.

Grimm, Ha, Klemm, Klevers, . . . '09-'11
Alim, Hecht, Jockers, Mayr, Mertens, . . .

Conclusions / Summary

- In the absence of new electroweak physics at a TeV, the 'vacuum stability scale' ($\lambda(\mu) = 0$) may be a crucial hint at new physics
- Well-motivated guess: SUSY broken with $\tan\beta = 1$ at this scale
- 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)
- The very same stringy symmetry (but in a different sector) may be crucial to maintain flatness in Fluxbrane inflation