The Higgs Mass in High-Scale (Remote) SUSY / String Theory

Arthur Hebecker (Heidelberg)

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

Outline

- 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
- Interesting fact: quartic coupling λ runs to zero below or near the Planck scale
- What happens at this distinguished energy scale?

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

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

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)

- 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

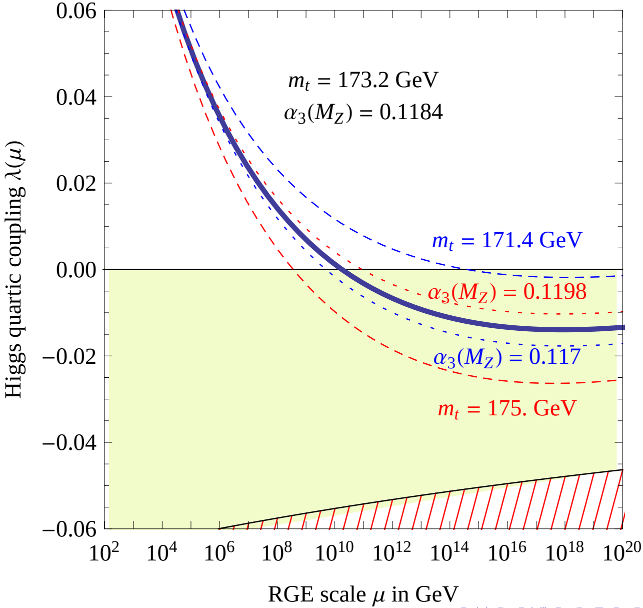
- Then it may be natural that $\lambda = 0$ emerges in the IR (i.e. at M_P) as a result of this strong dynamics

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

- The details are, however, more complicated... (especially the fine-tuning issue...)

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

$m_h = 126$ GeV



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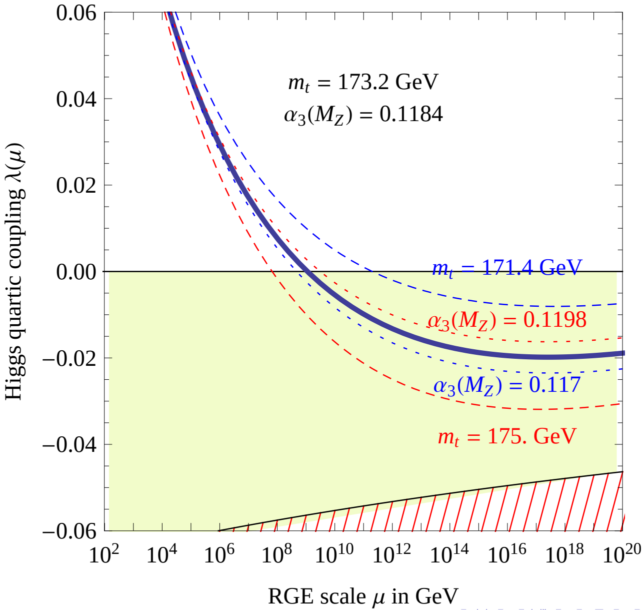
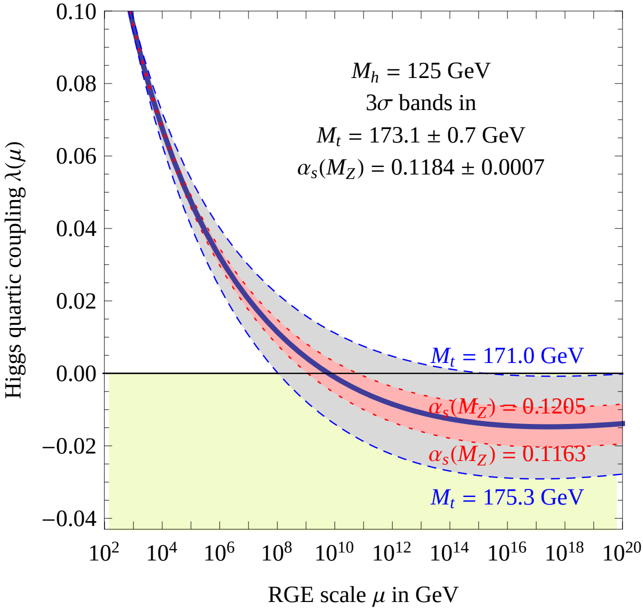


NNLO, from Degrassi et al., 1205.6497



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:

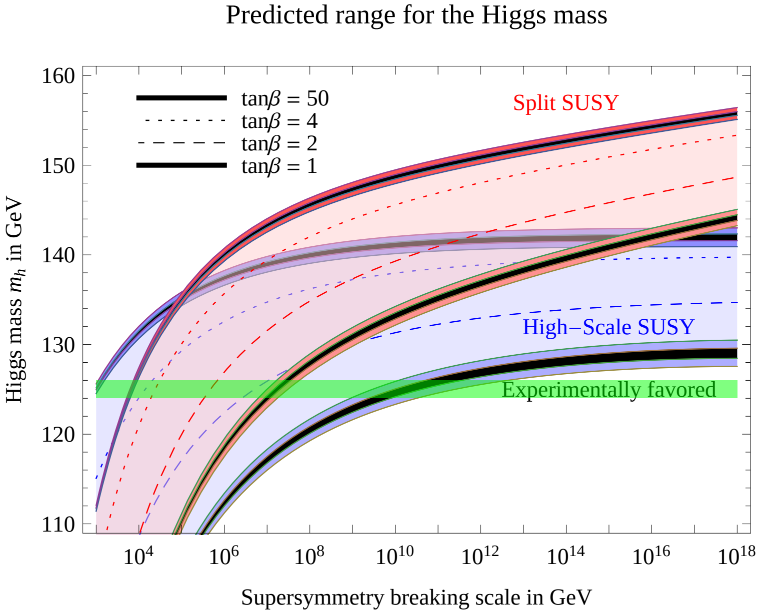
  Identify a special structure/symmetry leading to $\tan\beta = 1$ (i.e. to $\lambda = 0$)

- 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 '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 - 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,... Angus,... '12...'13

- 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:

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

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

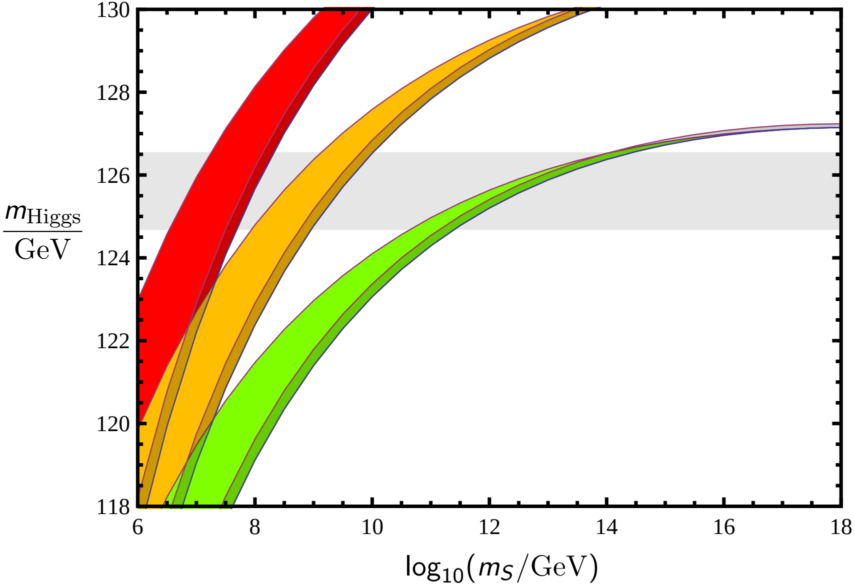
- Leading effects: y_t and gauge

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

- 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:

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

with

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

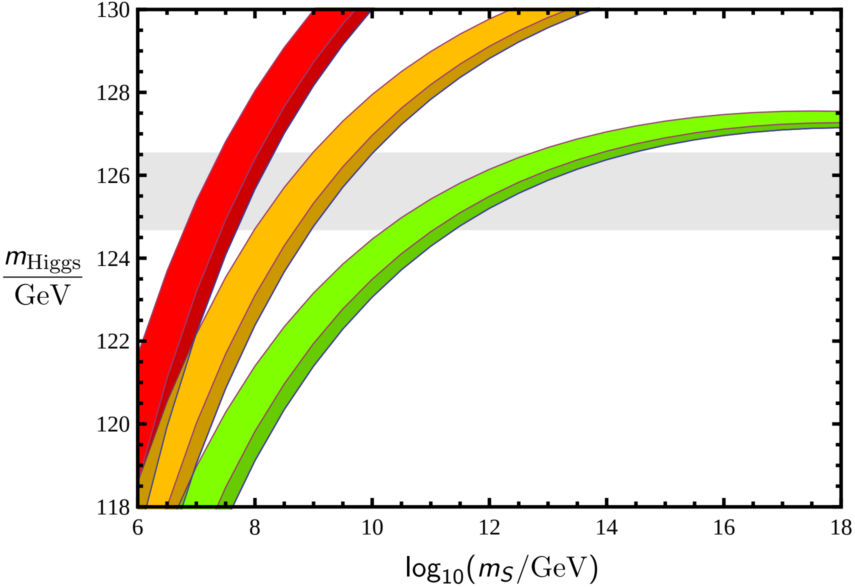
- For $X_t^2 = 0\ldots 6m_S^2$, they are in the range

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

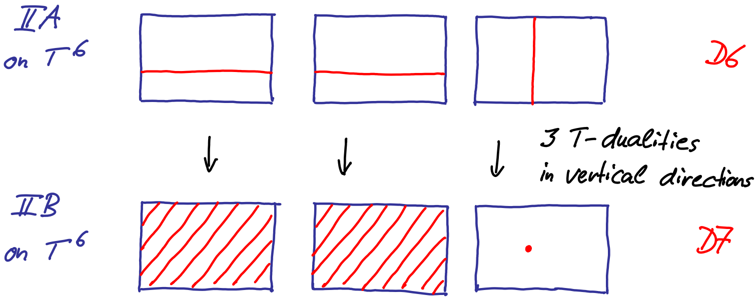
- These are qualitatively different from SUSY thresholds and should hence presumably not be absorbed in an 'effective SUSY breaking scale'

Drees, priv. comm.

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



Recall how T-duality with branes works...



...relating Wilson lines to brane positions

In CY-geometry, need Strominger-Yau-Zaslow conjecture...

Main new, stringy points analysed in our second paper:

- Deeper understanding of shift-symmetric Kähler potential on the IIB-side via mirror symmetry

  (including the surprising fact that D7 Wilson lines do not have a shift symmetry, while D7 positions do).

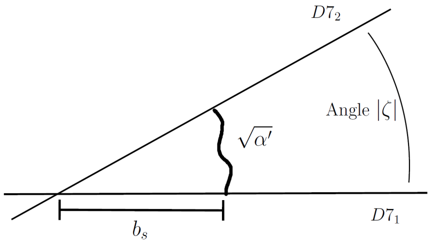
- There is an interesting class of F-theory GUTs with bulk Higgs

  Donagi/Wijnholt '11

- Here, the shift symmetry arises naturally and implies

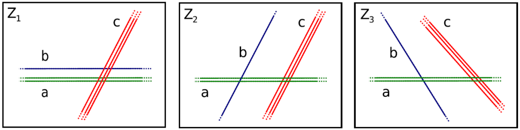
$$m_i^2 = 2m_{3/2}^2 \, .$$

- We have (at least parametrically) understood the transformation of the Higgs Kähler potential between bulk and brane Higgs....



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

- We have analysed the (highly non-trivial) requirements for a $\mathbb{Z}_2$-symmetry à la Ibanez et al.



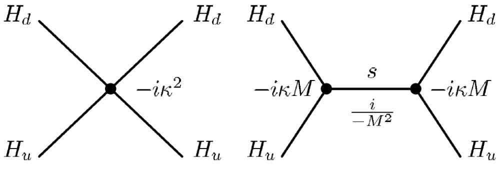
(One needs F-term breaking from brane angles, which requires a 'non-factorizable' brane geometry.)

From unstable high-scale to metastable low-scale theories

- So far, we argued that SUSY should appear at least at the scale μ_λ.
- In fact, it takes very little effort to avoid this naive expectation:
- 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...



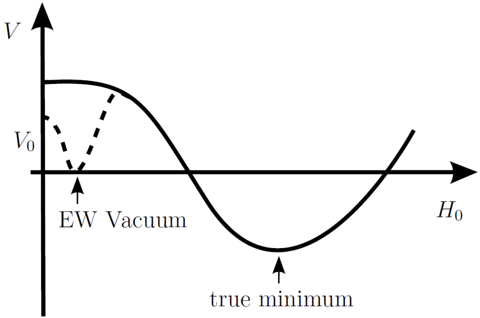
- However, adding additionally a negative soft mass-squared upsets this cancellation and gives a negative quartic effect:

Giudice/Strumia '11

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

- We propose to make this effect large and combine it with $\tan\beta = 1$.
- This leads to a theory unstable at the SUSY breaking scale.

- This leads to an interesting UV$\to$IR effective-theory running picture:



- ‘Our’ minimum is generated only radiatively, as λ runs from negative to positive values in a loop-calculation based on an unstable vacuum.

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

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

- It might be interesting to work out the cosmology (and maybe also the formal field theory) of this setting in more detail...

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

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

  (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

...and now for something completely different:

AdS/CFT for accelerator physics
or
Building the Tower of Babel

(1305.6311)

- One Planck-mass particle costs just $\sim$ 500 kWh.
- So why are our colliders so inefficient?
- Is a 'perfect' collider possible even in principle?
- Is there some no-go theorem in analogy to Carnot's?

(In other words: Are there limitations on the transformation of electrical energy into mass of heavy particles?)

Some (very incomplete) answers in AdS/CFT:

- Recall the Randall-Sundrum model
  (as a solution to the hierarchy problem and as a very simple version of AdS/CFT):

$$ds^2 = e^{2ky} dx^2 + dy^2$$

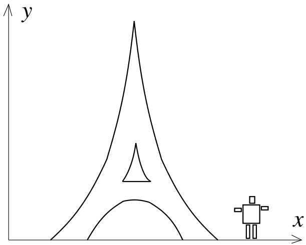
with

$$S = S_{bullk} + \int d^4x \sqrt{-g_{IR}} \mathcal{L}_{IR} + \int d^4x \sqrt{-g_{UV}} \mathcal{L}_{UV} \, .$$

- Imagine future technology wil allow us to penetrate the bulk and construct '5d robots'.

  (This corresponds to manipulating sub-TeV^{-1} structures in 4d language.)

5d-Towers are perfect ‘colliders’!

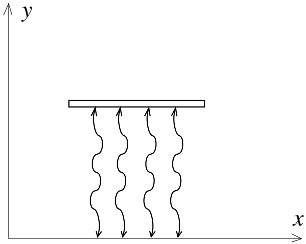


- Indeed, let’s assume there exist point-like particles of mass $\sim M$ in the bulk and on the UV brane (in the 5d metric).

- We produce such particles near the IR brane, ‘carry’ them up the tower, and let them decay on the UV brane.
- This means producing particles of mass $M \exp(ky_{UV})$ in 4d.

Limited height....

- The height of such towers is limited in principle.
- To understand the problem, let's first look at a toy model: a mirror (with elevator) supported by photon beam.



- For height y and 'structure scale' M, the beam density at the IR brane is...

$$\rho_{IR} \sim M^4 k e^{4ky} .$$

- Since the density can not exceed M^5, we have

$$e^{ky_{max}} \sim \left(\frac{M}{k}\right)^{1/4} .$$

- Thus, a perfect 'collider' with energy reach $M(M/k)^{1/4}$ exists.

- Note: In addition, 5d gravity has to be sufficiently weak to avoid black hole formation in the lower region of the beam:

$$M_5^3 > M^5/k^2 .$$

Optimal tower

- Now let's build an optimal (tapering) tower from the strongest available 5d material (highest p/ρ).
- We get a differential equation for $A(y)$ from
$$F(y) = pA(y)$$
and
$$F(y) = F(y + \delta y) \cdot (1 + k\delta y) + k\rho A(y)\delta y\,.$$
- The solution is
$$A(y) = A_0 e^{-(1+\rho/p)ky}\,.$$
- This analysis works only for 'thin' towers, i.e. if
$$-[A^{1/3}(y)]' \ll 1\,.$$
- Together with the requirement of a minimal thickness M at the upper end, this gives...

$$e^{ky_{max}} \sim \left(\frac{M}{k}\right)^{\frac{3}{1+\rho/p}} ,$$

which is very similar to the mirror-result.

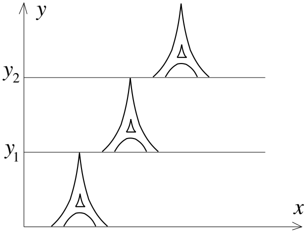
- In both cases, the energy-reach falls as M/k decreases.
- Recall that in 'proper' AdS/CFT, the 4d theory becomes weakly-coupled as the curvature scale k grows:

$$\lambda \sim g_{YM}^2 N \sim \left(\frac{M_s}{k}\right)^4 .$$

- Thus, we might expect a no-go theorem for perfect colliders in 4d weakly-coupled QFT.

Some further 'duality' ideas...

(I) Tower-cascade vs. collider-cascade...



(II) A 'spherical standing wave' in 4d at weak coupling can (presumably) not work.

(III) Let us assume (ignoring all technical problems) a very long linear accelerator (built e.g. in open space)

We also ignore all 'gravity problems'

Casher/Nussinov '95, '97

Then there is still a limited 'beam focusing scale' m and hence a limited efficiency

$$\eta \sim m^2/M_{UV}^2 \, .$$

The efficiency drops as M_{UV} exceeds the 'structure scale' m.

This is as in our 'holographic collider' approach.

Conclusions

- Perfect (holographic) ‘colliders’ are possible, but the energy reach is limited.
- Unfortunately, a general Carnot-type no-go theorem for energy conversion into heavy-particle-mass is still far away.
- Can (holographic) entanglement entropy be helpful?

Ryu/Takayanagi ’06
Lello/Boyanovsky/Holman ’13

- Is entropic (5d) gravity relevant?

Jacobson ’95; Verlinde ’‘10

- If a small dS-radius constrains linear colliders and 5d gravity constrains ‘tower colliders’, could there be total UV-protection?

Dvali/Gomez ’10