Aspects of string phenomenology in the LHC era

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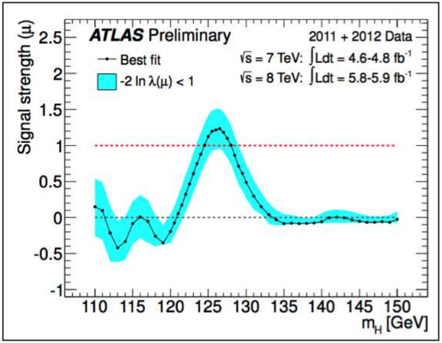
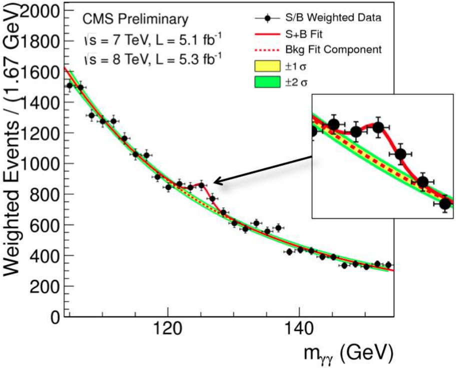
Planck 2013 - Bonn, 20-24 May 2013

- High string scale, SUSY and 125 GeV Higgs
- Live with the hierarchy and extra $U(1)$'s
- Low scale strings and extra dimensions

Higgs boson discovery





$m_H = 125.5 \pm 0.2\,(\mathrm{stat.}) \pm 0.5\,(\mathrm{syst.})$

$m_H = 125.7 \pm 0.3 \pm 0.3$ GeV

Beyond the Standard Model of Particle Physics: driven by the mass hierarchy problem

Standard picture: low energy supersymmetry

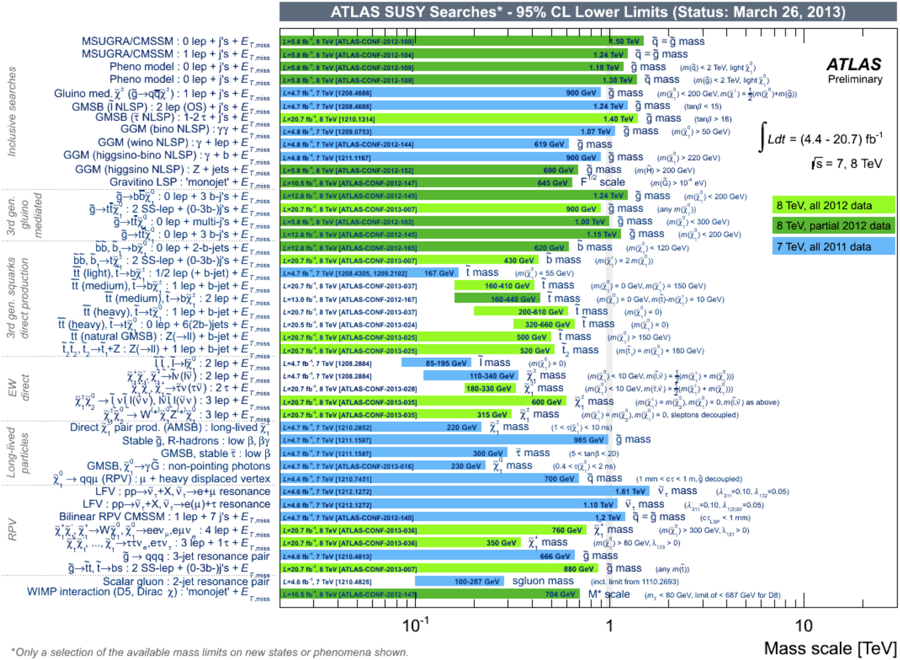
Natural framework: Heterotic string (or high-scale M/F) theory

Advantages:

- natural elementary scalars
- gauge coupling unification
- LSP: natural dark matter candidate
- radiative EWSB

Problems:

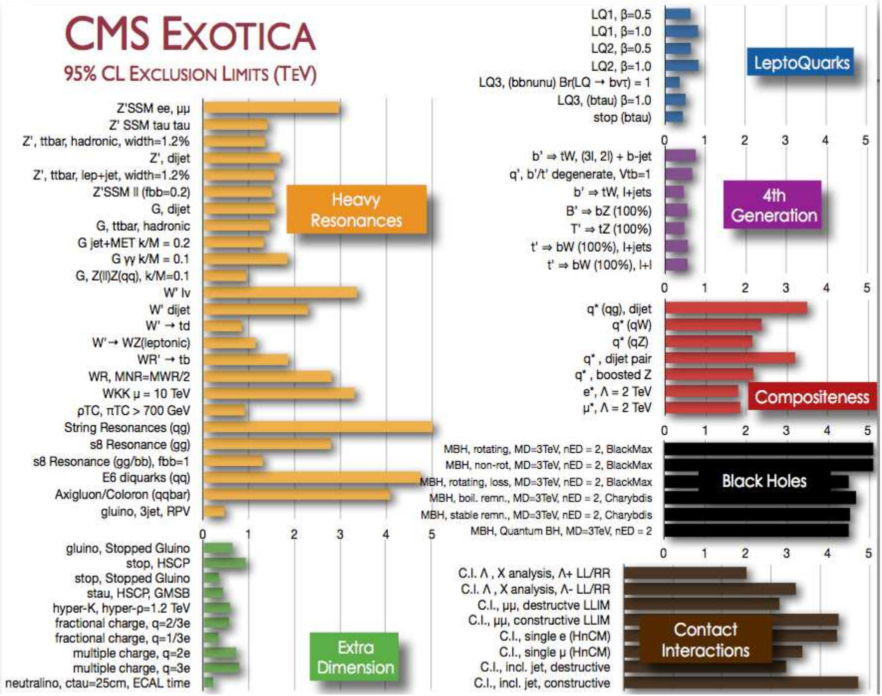
- too many parameters: soft breaking terms
- MSSM : already a % - ‰ fine-tuning 'little' hierarchy problem



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

CMS EXOTICA

95% CL EXCLUSION LIMITS (TEV)



Remarks on the value of the Higgs mass ~ 125 GeV

- consistent with expectation from precision tests of the SM
- favors perturbative physics   quartic coupling $\lambda = m_H^2/v^2 \simeq 1/8$

Window to new physics

- compatible with supersymmetry

  but appears fine-tuned in its minimal version [8]

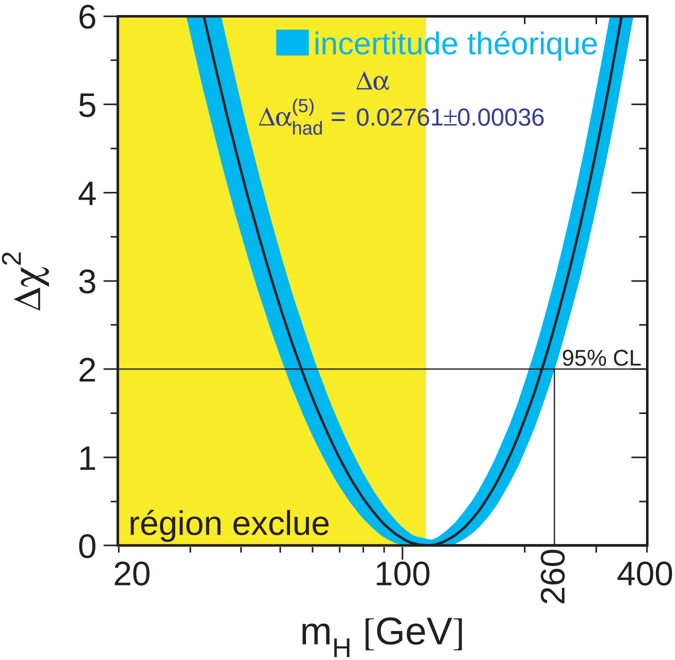
  early to draw a general conclusion before LHC13/14

  e.g. an extra singlet or split families can alleviate the fine tuning [9]

- very important to measure its properties and couplings [13]

  any deviation of its couplings to top, bottom and EW gauge bosons

  implies new light states involved in the EWSB altering the fine-tuning


6
5
4
3
2
1
0
$\Delta\chi^2$
🟦 incertitude théorique
$\Delta\alpha$
$\Delta\alpha^{(5)}_{had} = 0.02761 \pm 0.00036$
95% CL
région exclue
20
100
260
400
m_H [GeV]

Fine-tuning in MSSM

Upper bound on the lightest scalar mass:

$$m_h^2 \lesssim m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2}\right)\right] \lesssim (130\,GeV)^2$$

$m_h \simeq 126$ GeV $\Rightarrow m_{\tilde{t}} \simeq 3$ TeV or $A_t \simeq 3 m_{\tilde{t}} \simeq 1.5$ TeV

$\Rightarrow$ % to a few ‰ fine-tuning

minimum of the potential: $m_Z^2 = 2\dfrac{m_1^1 - m_2^2 \tan_\beta^2}{\tan^2\beta - 1} \sim -2m_2^2 + \cdots$

RG evolution: $m_2^2 = \; m_2^2(M_{\rm GUT}) - \dfrac{3\lambda_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln\dfrac{M_{\rm GUT}}{m_{\tilde{t}}} + \cdots$ [23]

$$\sim m_2^2(M_{\rm GUT}) - \mathcal{O}(1) m_{\tilde{t}}^2 + \cdots$$ [6]

MSSM with dim-5 and 6 operators

I.A.-Dudas-Ghilencea-Tziveloglou '08, '09, '10

parametrize new physics above MSSM by higher-dim effective operators

relevant super potential operators of dimension-5:

$$\mathcal{L}^{(5)} = \frac{1}{M}\int d^2\theta \left(\eta_1 + \eta_2 S\right)(H_1 H_2)^2$$

η_1 : generated for instance by a singlet

$$W = \lambda\sigma H_1 H_2 + M\sigma^2 \quad \rightarrow \quad W_{\rm eff} = \frac{\lambda^2}{M}\,(H_1 H_2)^2$$

Strumia '99 ; Brignole-Casas-Espinosa-Navarro '03
Dine-Seiberg-Thomas '07

η_1 : corresponding soft breaking term spurion $S \equiv m_S\,\theta^2$

Physical consequences of MSSM$_5$: Scalar potential

$$\mathcal{V} = m_1^2|h_1|^2 + m_2^2|h_2|^2 + B\mu(h_1 h_2 + \mathrm{h.c.}) + \frac{g_2^2 + g_Y^2}{8}\left(|h_1|^2 - |h_2|^2\right)^2$$
$$+ \left(|h_1|^2 + |h_2|^2\right)\left(\eta_1 h_1 h_2 + \mathrm{h.c.}\right) + \frac{1}{2}\left[\eta_2 (h_1 h_2)^2 + \mathrm{h.c.}\right] + \mathcal{O}\left(\eta_i^2\right)$$

- $\eta_{1,2} \Rightarrow$ quartic terms along the D-flat direction $|h_1| = |h_2|$
- potential stability $\Rightarrow \eta_2 \geq 4|\eta_1|$

requiring η-corrections to be smaller than MSSM mass matrix elements $\Rightarrow$

only η_2 can change the tree-level bound $m_h \leq m_Z$ but marginally

Relevance of dim-6 operators

Relaxing the condition on potential positivity: guaranteed by dim-6 ops

only one dim-6 along the D-flat direction induced by dim-5: $\propto \eta_1^2$

$$W = \eta_1 (H_1 H_2)^2 \longrightarrow V = \left| \frac{\partial W}{\partial H_i} \right|^2 \sim \eta_1^2 \, |H_1 H_2|^2 \left(|H_1|^2 + |H_2|^2 \right)$$

- tree-level mass can increase significantly
- bigger parameter space for LSP being dark matter

Bernal-Blum-Nir-Losada '09

MSSM Higss with dim-6 operators

dim-6 operators can have an independent scale from dim-5

Classification of all dim-6 contributing to the scalar potential

(without $\mathrm{SU}\!\!\!/\mathrm{SY}$) $\Rightarrow$

large $\tan\beta$ expansion: $\delta_6 m_h^2 = \underset{\nearrow}{f}\, v^2 + \cdots$

constant receiving contributions from several operators

$f \sim f_0 \times \left(\mu^2/M^2,\ m_S^2/M^2,\ \mu m_S/M^2,\ v^2/M^2\right)$

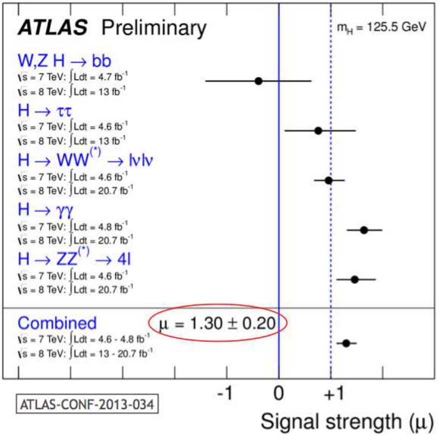
$m_S = 1$ TeV, $M = 10$ TeV, $f_0 \sim 1 - 2.5$ for each operator

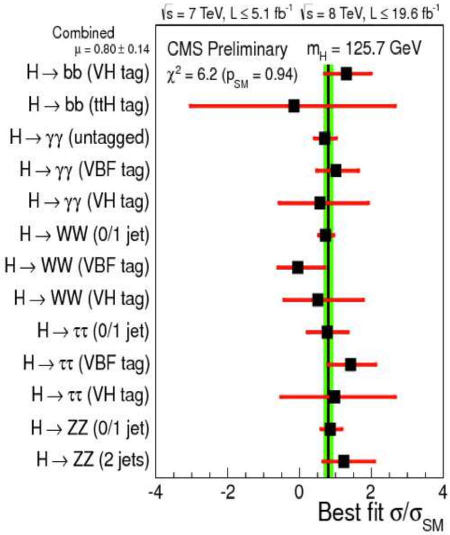
$\Rightarrow m_h \simeq 103 - 119$ GeV

$\Rightarrow$ MSSM with dim-5 and dim-6 operators:

possible resolution of the MSSM fine-tuning problem [6]

Couplings of the new boson vs SM



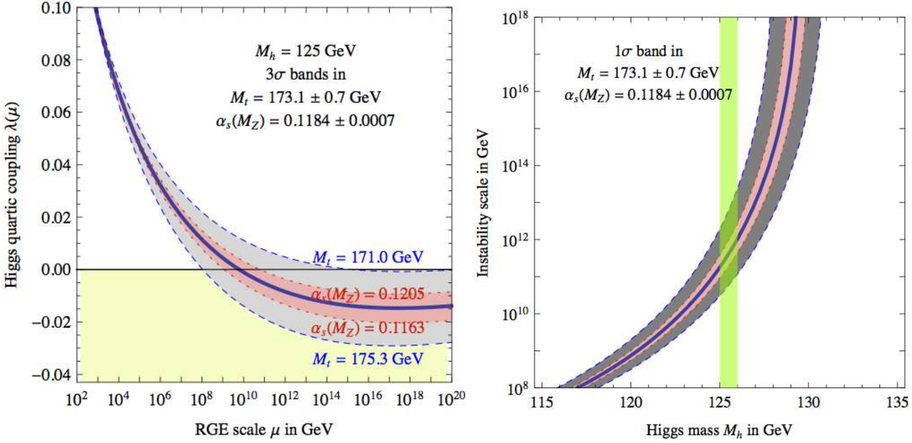


exclusion : spin 2 and pseudoscalar at $\gtrsim$ 95% CL

Agreement with Standard Model expectation at $\sim 2\,\sigma$

Can the SM be valid at high energies?

Degrassi-Di Vita-Elias Miró-Espinosa-Giudice-Isidori-Strumia '12



Instability of the SM Higgs potential ⇒ metastability of the EW vacuum

If the weak scale is tuned ⇛ split supersymmetry is a possibility

Arkani Hamed-Dimopoulos '04, Giudice-Romaninio '04

- natural splitting: gauginos, higgsinos carry R-symmetry, scalars do not
- main good properties of SUSY are maintained

  gauge coupling unification and dark matter candidate
- also no dangerous FCNC, CP violation, . . .
- experimentally allowed Higgs mass ⇛ 'mini' split

  $m_S \sim$ few - thousands TeV

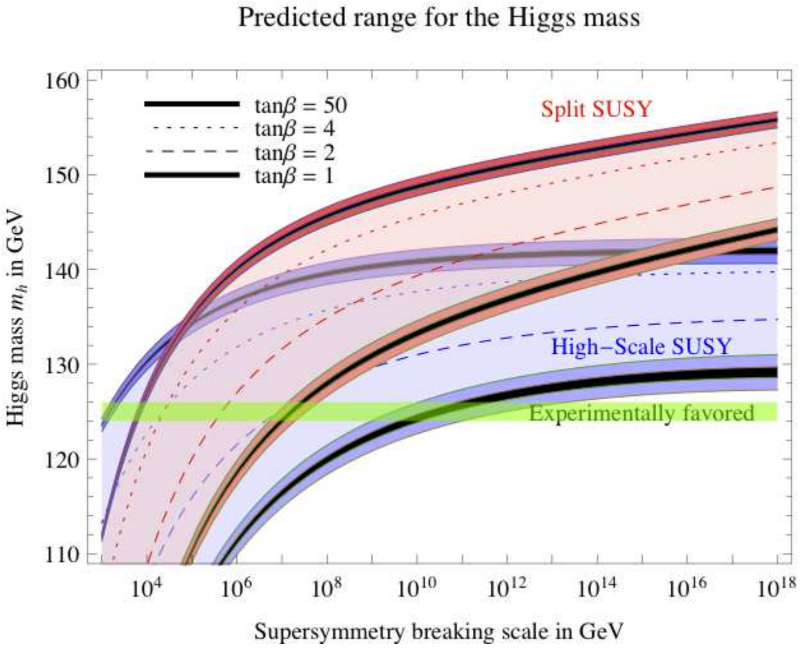
  gauginos: a loop factor lighter than scalars ($\sim m_{3/2}$)
- natural string framework: intersecting (or magnetized) branes

  IA-Dimopoulos '04

  D-brane stacks are supersymmetric with massless gauginos

  intersections have chiral fermions with broken SUSY & massive scalars

Giudice-Strumia '11



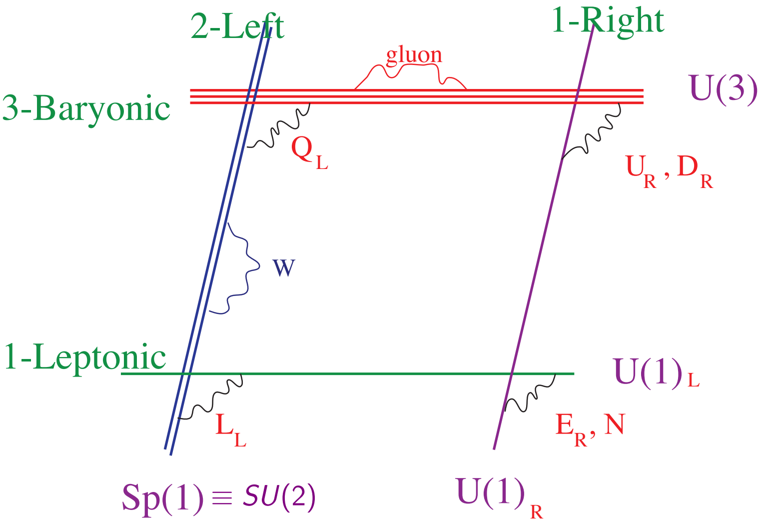
An extra $U(1)$ can also cure the instability problem

Anchordoqui-IA-Goldberg-Huang-Lüst-Taylor-Vlcek '12

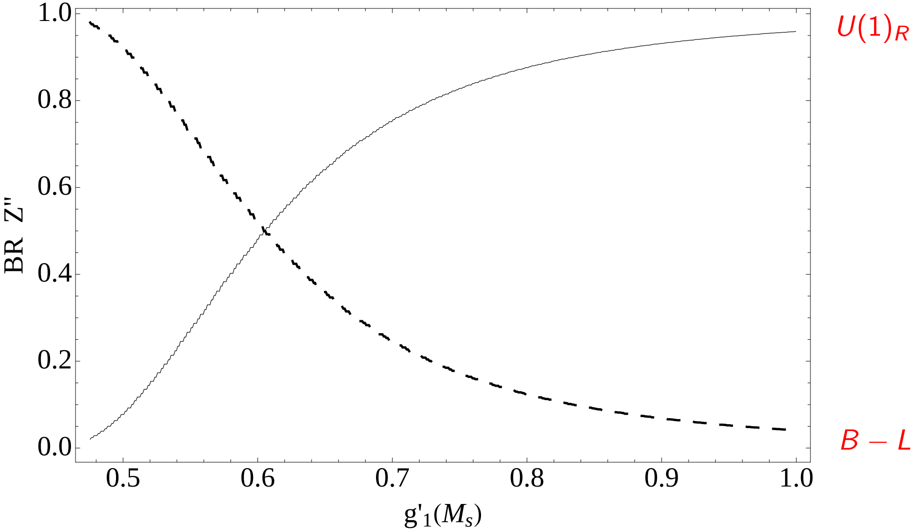
- B anomalous and superheavy
- $B - L$ massless at the string scale (no associated 6d anomaly)

  but broken at TeV by a scalar VEV with the quantum numbers of N_R
- L-violation from higher-dim operators suppressed by the string scale
- $U(3)$ unification, Y combination $\Rrightarrow$ 2 parameters: 1 coupling + $m_{Z''}$
- perturbativity $\Rrightarrow 0.5 \lesssim g_{U(1)_R} \lesssim 1$
- present LHC limits: $m_{Z''} \gtrsim 3$ - 4 TeV (for $Z'' \simeq B - L$ or $U(1)_R$)
- interesting LHC phenomenology and cosmology [20]

Standard Model on D-branes : SM^{++}



$U(1)^3 \Rightarrow$ hypercharge + B, L [27]


BR Z''
1.0
0.8
0.6
0.4
0.2
0.0
0.5
0.6
0.7
0.8
0.9
1.0
$g'_1(M_s)$
$U(1)_R$
$B-L$

- Rotation of $U(1)$'s from the string to low energy basis Z, Z', Z'':

  completely fixed in terms of the couplings

  - Decoupling of anomalous $Z' \simeq B$
  - Z'' linear combination of $B - L$ and $U(1)_R$

- Recent cosmological observations indicate extra relativistic component

  dark radiation parametrized by an effective ν-number close to 4 *

  $\rightarrow$ use the 3 ν_R's interacting with SM fermions via Z''

  data: their decoupling during the quark-hadron transition

  $\Rightarrow 3.5 \lesssim M_{Z''} \lesssim 7$ TeV (within LHC14 discovery potential)

  * before Planck results

Stability analysis in (non-susy) SM^{++} **AAGHLTV '12**

Scalar potential:

$$V\left(H, H''\right) = \mu^2 \left|H\right|^2 + {\mu'}^2 \left|H''\right|^2 + \lambda_1 \left|H\right|^4 + \lambda_2 \left|H''\right|^4 + \lambda_3 \left|H\right|^2 \left|H''\right|^2$$

5 parameters $\Rightarrow v, m_h, v'', m_{h''}$ + a scalar mixing angle α

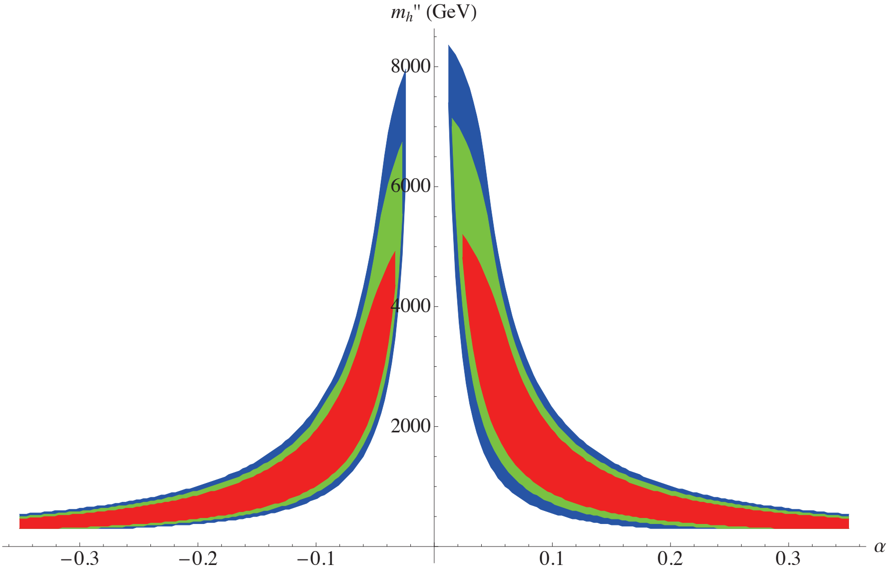
$\Rightarrow$ 3 free parameters : $m_{h''}, \alpha, v'' \leftrightarrow M_{Z''}$

Stability conditions: $\lambda_1 > 0$, $\lambda_2 > 0$, $\lambda_1\lambda_2 > \frac{1}{4}\lambda_3^2$

RGE analysis up to $M_s \Rightarrow$ stability is possible in SM^{++}

for $0.02 \lesssim |\alpha| \lesssim 0.35$ and $500\ \mathrm{GeV} \lesssim m_{h''} \lesssim 5\ \mathrm{TeV}$

$M_{Z''} = 4.5$ TeV; $M_s = 10^{14},\ 10^{16},\ 10^{19}$ GeV



Alternative answer: Low UV cutoff $\Lambda \sim$ TeV

- low scale gravity $\Rightarrow$ extra dimensions: large flat or warped

- low string scale $\Rightarrow$ low scale gravity, ultra weak string coupling

$M_s \sim 1$ TeV $\Rightarrow$ volume $R_\perp^n = 10^{32}\, l_s^n$ ($R_\perp \sim .1 - 10^{-13}$ mm for $n = 2 - 6$)

- spectacular model independent predictions

- radical change of high energy physics at the TeV scale

Moreover no little hierarchy problem:

radiative electroweak symmetry breaking with no logs [8]

$\Lambda \sim$ a few TeV and $m_H^2 =$ a loop factor $\times \Lambda^2$

But unification has to be probably dropped

New Dark Matter candidates e.g. in the extra dims

Origin of EW symmetry breaking?

possible answer: radiative breaking I.A.-Benakli-Quiros '00

$V = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2$

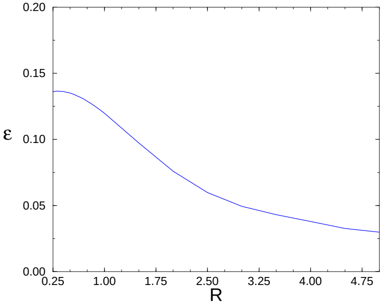
$\mu^2 = 0$ at tree but becomes < 0 at one loop non-susy vacuum

simplest case: one scalar doublet from the same brane

$\Rightarrow$ tree-level V same as susy: $\lambda = \frac{1}{8}(g_2^2 + g'^2)$ D-terms

$\mu^2 = -g^2 \varepsilon^2 M_s^2 \leftarrow$ effective UV cutoff

$$\varepsilon^2(R) = \frac{R^3}{2\pi^2} \int_{\underset{\text{IR}\,\nearrow}{0}}^{\overset{\text{UV}\,\searrow}{\infty}} dl\, l^{3/2} \underset{\searrow\, 1}{\overset{\nearrow\, e^{-\pi l}}{\frac{\theta_2^4}{16 l^4 \eta^{12}}}} \left(il + \frac{1}{2}\right) \sum_n n^2 e^{-2\pi n^2 R^2 l}$$



$R \to 0$: $\varepsilon(R) \simeq 0.14$ large transverse dim $R_\perp = l_s^2/R \to \infty$

$R \to \infty$: $\varepsilon(R) M_s \sim \varepsilon_\infty / R$ $\varepsilon_\infty \simeq 0.008$ UV cutoff: $M_s \to 1/R$

Higgs scalar = component of a higher dimensional gauge field

$\Rightarrow \varepsilon_\infty$ calculable in the effective field theory

$\lambda = g^2/4 \sim 1/8 \quad \Rightarrow \quad M_H \simeq v/2 = 125$ GeV

M_s or $1/R \sim$ a few or several TeV [29]

Accelerator signatures: 4 different scales

- Gravitational radiation in the bulk ⇛ missing energy

  present LHC bounds: $M_* \gtrsim 2.5 - 4$ TeV

- Massive string vibrations ⇛ e.g. resonances in dijet distribution

$$M_j^2 = M_0^2 + M_s^2\, j \quad ; \quad \text{maximal spin} : j+1$$

  higher spin excitations of quarks and gluons with strong interactions

  present LHC limits: $M_s \gtrsim 5$ TeV

- Large TeV dimensions ⇛ KK resonances of SM gauge bosons I.A. '90

$$M_k^2 = M_0^2 + k^2/R^2 \ ; \ k = \pm 1, \pm 2, \ldots$$

  experimental limits: $R^{-1} \gtrsim 0.5 - 4$ TeV (UED - localized fermions)

- extra $U(1)$'s and anomaly induced terms

  masses suppressed by a loop factor from M_s

Extra $U(1)$'s and anomaly induced terms

masses suppressed by a loop factor

usually associated to known global symmetries of the SM

(anomalous or not) such as (combinations of)

Baryon and Lepton number, or PQ symmetry

Two kinds of massive $U(1)$'s: I.A.-Kiritsis-Rizos '02

- 4d anomalous $U(1)$'s: $M_A \simeq g_A M_s$
- 4d non-anomalous $U(1)$'s: (but masses related to 6d anomalies)

  $M_{NA} \simeq g_A M_s V_2 \leftarrow$ (6d→4d) internal space $\Rightarrow M_{NA} \geq M_A$

  or massless in the absence of such anomalies [18]

TeV string scale

Anchordoqui-IA-Goldberg-Huang-Lüst-Taylor '11

- B and L become massive due to anomalies

  Green-Schwarz terms

- the global symmetries remain in perturbation

  - Baryon number $\Rrightarrow$ proton stability

  - Lepton number $\Rrightarrow$ protect small neutrino masses

  no Lepton number $\Rrightarrow \frac{1}{M_s} LLHH \rightarrow$ Majorana mass: $\frac{\langle H \rangle^2}{M_s} LL$

  $\nwarrow$ $\sim$ GeV

- $B, L \Rrightarrow$ extra Z's

  with possible leptophobic couplings leading to CDF-type Wjj events

  $Z' \simeq B$ lighter than 4d anomaly free $Z'' \simeq B - L$

Conclusions

- Confirmation of the EWSB scalar at the LHC:

  important milestone of the LHC research program
- Precise measurement of its couplings is of primary importance
- Hint on the origin of mass hierarchy and of BSM physics
  - natural or unnatural SUSY?
  - low string scale in some realization?
  - something new and unexpected?
- LHC enters a new era with possible new discoveries