Aspects of string phenomenology in the LHC era

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4th Bethe Center Workshop on Unification and String Theory

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- High string scale, SUSY and 125 GeV Higgs
- Extra $U(1)$'s
- Low scale strings and extra dimensions
- Tiny string coupling and linear dilaton background

Connect string theory to the real world:

What is the value of the string scale M_s ?

- arbitrary parameter : Planck mass $M_P \longrightarrow$ TeV

- physical motivations $\Rrightarrow$ favored energy regions:

- High : $\begin{cases} M_P^* \simeq 10^{18} \text{ GeV} & \text{Heterotic scale} \\ M_{\rm GUT} \simeq 10^{16} \text{ GeV} & \text{Unification scale} \end{cases}$

- Intermediate : around 10^{11} GeV ($M_s^2/M_P \sim$ TeV)

  SUSY breaking, strong CP axion, see-saw scale

- Low : TeV (hierarchy problem)

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

Standard picture: low energy supersymmetry

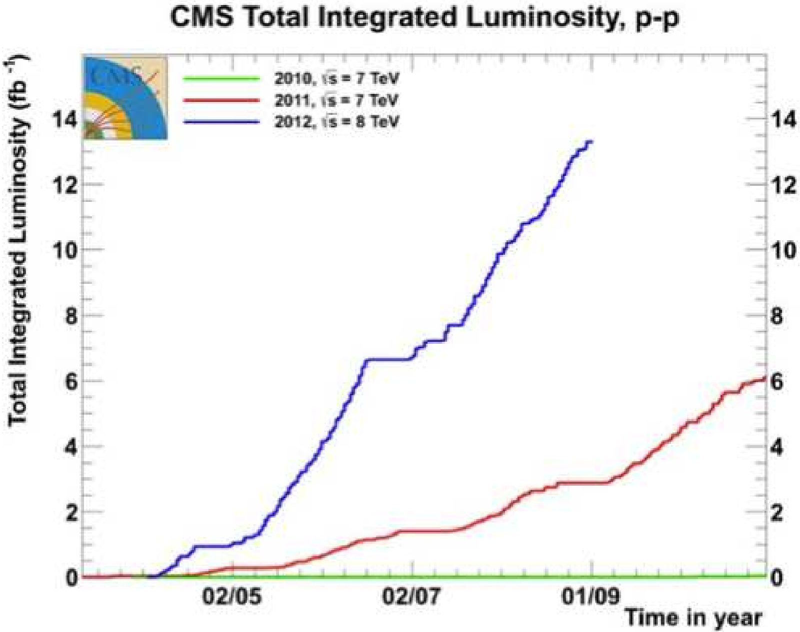
Natural framework: Heterotic string (or high-scale M/F) theory

Advantages:

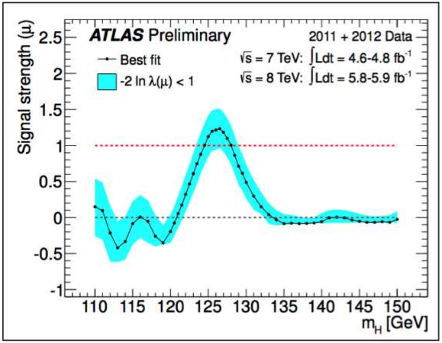
- natural elementary scalars
- gauge coupling unification
- LSP: natural dark matter candidate
- radiative EWSB

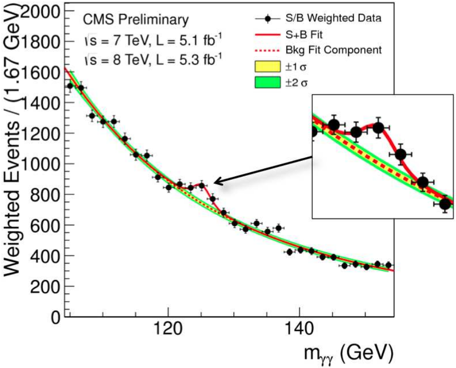
Problems:

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


CMS Total Integrated Luminosity, p-p
2010, √s = 7 TeV
2011, √s = 7 TeV
2012, √s = 8 TeV
Total Integrated Luminosity (fb⁻¹)
0
2
4
6
8
10
12
14
02/05
02/07
01/09
Time in year

Higgs search at the LHC





$m_H = 126 \pm 0.4\,(\mathrm{stat.}) \pm 0.4\,(\mathrm{syst.})$

$5.9\ \sigma$

$m_H = 125.3 \pm 0.4 \pm 0.5$ GeV

$5\ \sigma$ significance

Remarks

Higgs-like particle discovery around 125 GeV :

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

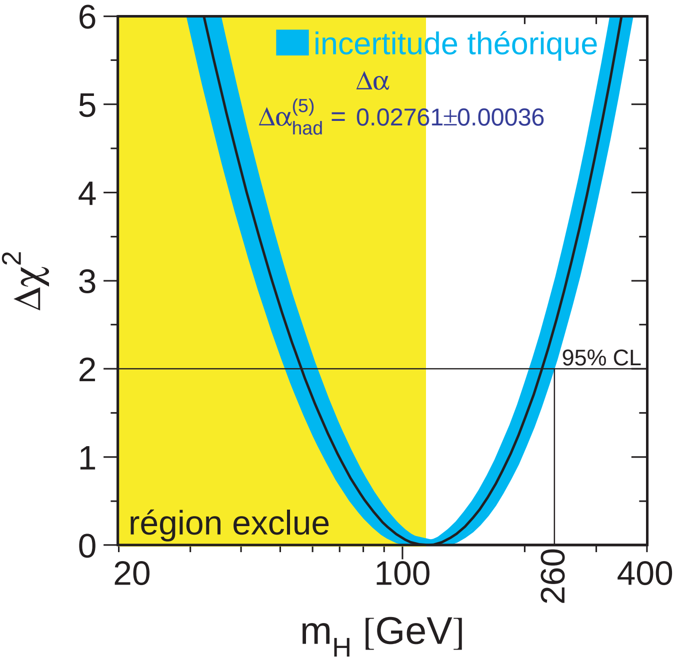
If confirmed :

- supersymmetry becomes ‘severely’ fine-tuned, in its minimal version
- but still early to draw a general conclusion before LHC13/14

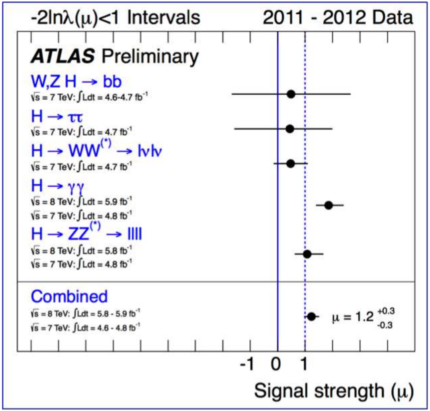
  an extra singlet or split families can remediate the fine tuning to $\lesssim 10$
- very important to measure Higgs couplings [8]

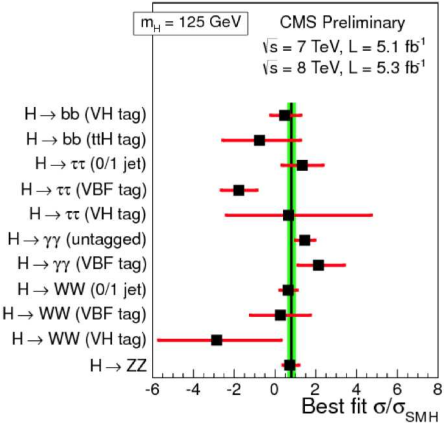
  any deviation of its couplings to top, bottom and EW gauge bosons

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


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

Couplings of the new boson vs SM Higgs

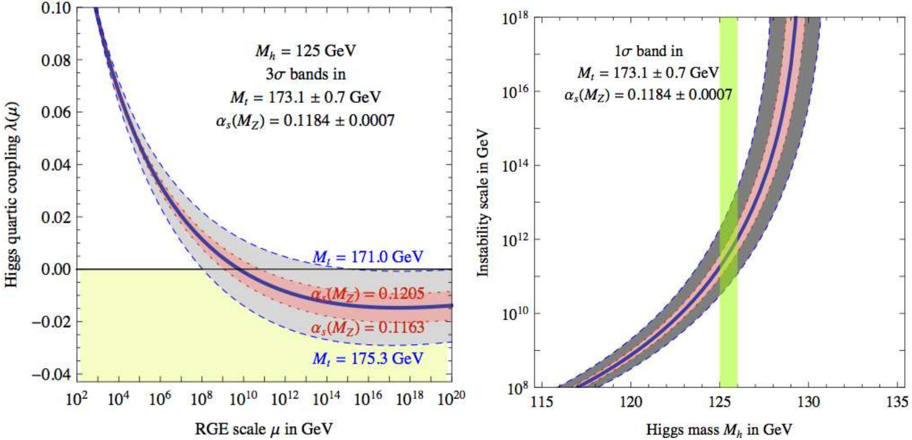




Agreement with Standard Model Higgs expectation at 1.5 σ

Can the SM be valid at high energies?

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



Instability of the SM Higgs potential $\Rightarrow$ metastability of the EW vacuum

If the weak scale is tuned $\Rightarrow$ 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 $\Rightarrow$ 'moderate' split

  $m_S \sim$ few - thousands TeV

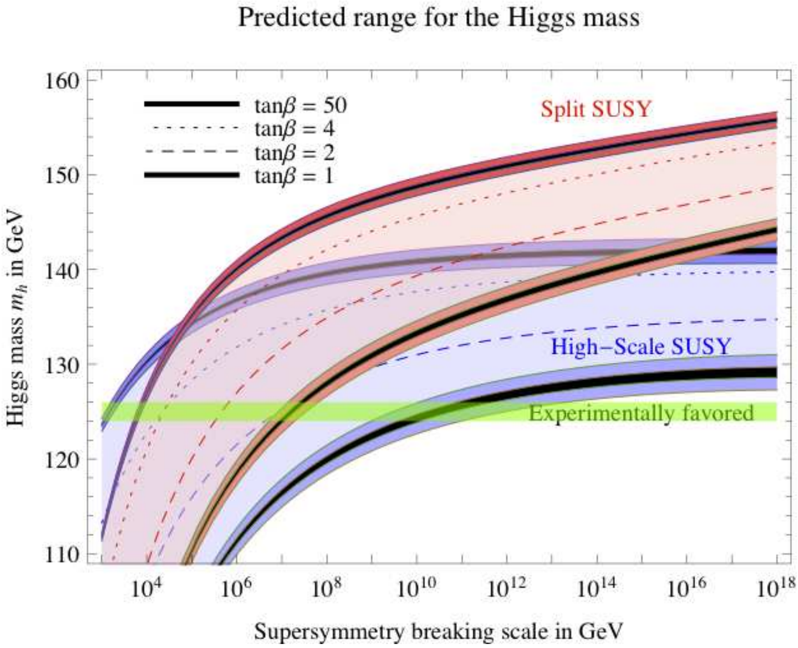
  gauginos: a loop factor lighter than scalars ($\sim m_{3/2}$)
- natural string framework: intersecting (or magnetized) branes

  IA-Dimopoulos '04

  D-brane stacks are supersymmetric with massless gauginos

  intersections have chiral fermions with broken SUSY & massive scalars

Giudice-Strumia '11



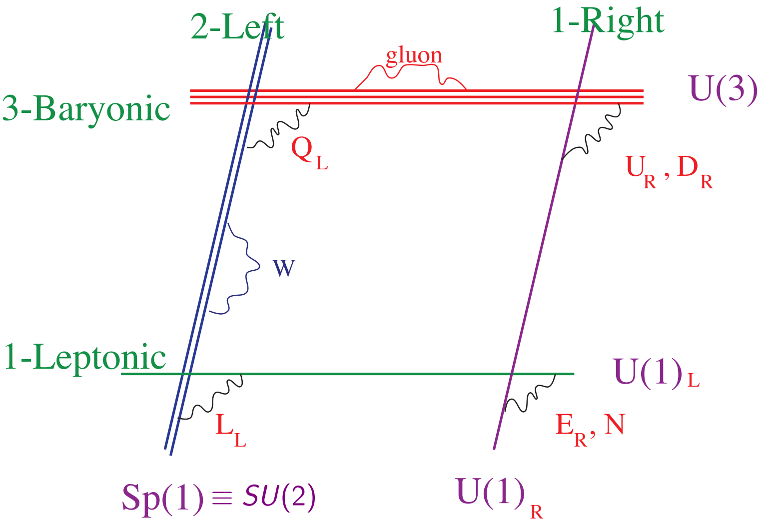
An extra $U(1)$ can also cure the instability problem

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

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



$U(1)^3$: hypercharge + B, L global

- 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 $U(1)_R$

- LHC14 discovery potential: $M_{Z''}$ up to ~ 5 TeV

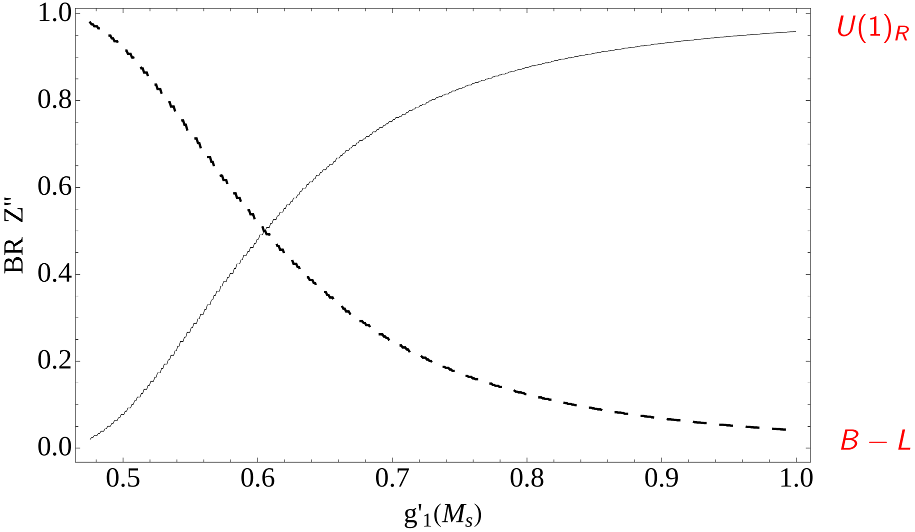
Recent cosmological observations indicate an extra relativistic component

dark radiation parametrized by an effective neutrino 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

$$\Rightarrow 3.5 \lesssim M_{Z''} \lesssim 7 \text{ TeV}$$


1.0
0.8
0.6
0.4
0.2
0.0
BR Z''
0.5
0.6
0.7
0.8
0.9
1.0
g'1(Ms)
U(1)R
B − L

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 Higgs mixing angle α

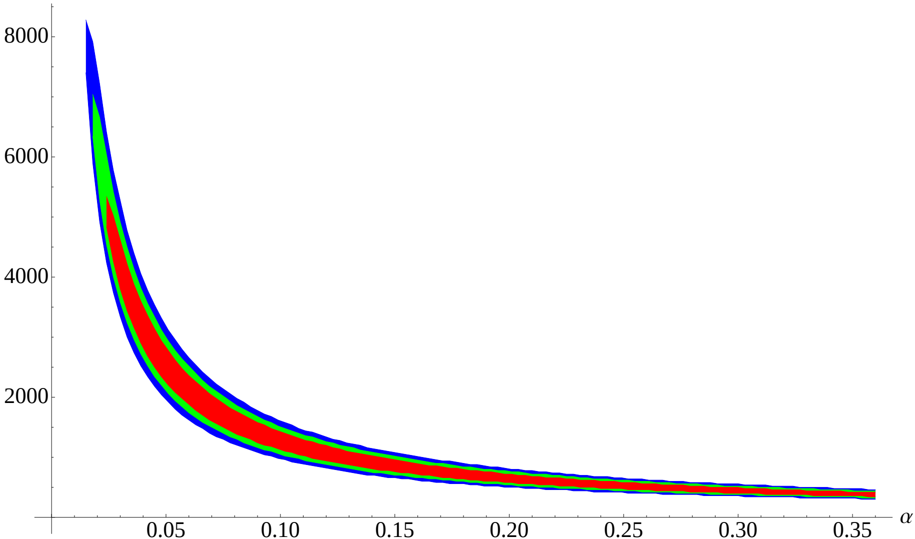
$\Rightarrow$ 3 free parameters : $m_{h''}, \alpha, v'' \leftrightarrow M_{Z''}$

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

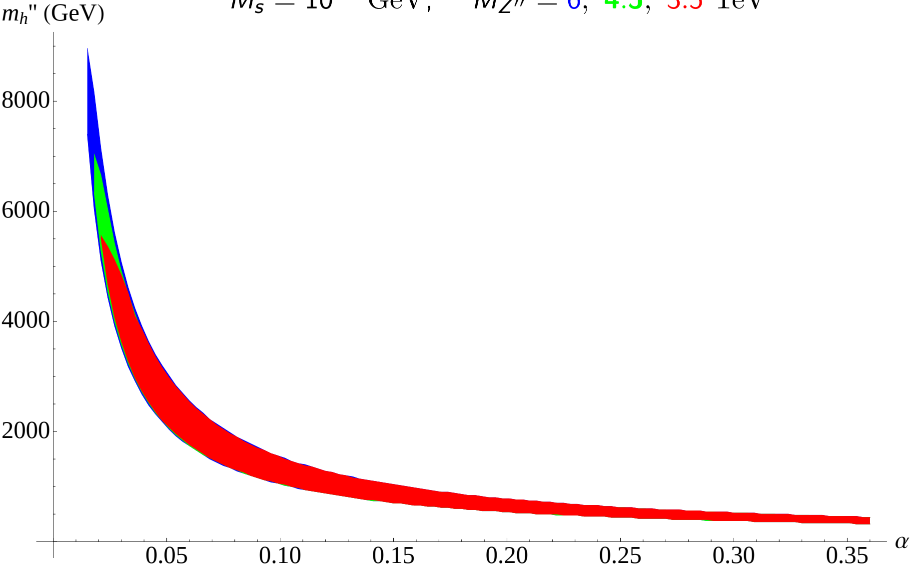
RGE analysis up to $M_s \Rightarrow$ stability is possible in SM^{++}

for $0.05 \lesssim \alpha \lesssim 0.35$ 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



$M_s = 10^{16}$ GeV; $M_{Z''} = 6,\ 4.5,\ 3.5$ TeV



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

Experimentally testable framework:

- 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

$\Lambda \sim$ a few TeV and $m_H^2 =$ a loop factor $\times \Lambda^2$ [21]

But unification has to be probably dropped

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

Framework of type I string theory $\Rightarrow$ D-brane world

I.A.-Arkani-Hamed-Dimopoulos-Dvali '98

- gravity: closed strings propagating in 10 dims
- gauge interactions: open strings with their ends attached on D-branes

Dimensions of finite size: n transverse $6-n$ parallel

calculability $\Rightarrow R_\parallel \simeq l_{\rm string}$; $R_\perp$ arbitrary

$M_P^2 \simeq \frac{1}{g_s^2} M_s^{2+n} R_\perp^n$ $g_s = \alpha$: weak string coupling

Planck mass in $4+n$ dims: M_*^{2+n}

small M_s/M_P : extra-large $R_\perp$

$M_s \sim 1$ TeV $\Rightarrow R_\perp^n = 10^{32}\ l_s^n$ [30]

$$R_\perp \sim .1 - 10^{-13}\ \text{mm for } n = 2-6$$

distances $< R_\perp$: gravity $(4+n)$-dim $\rightarrow$ strong at 10^{-16} cm

Origin of EW symmetry breaking?

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

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

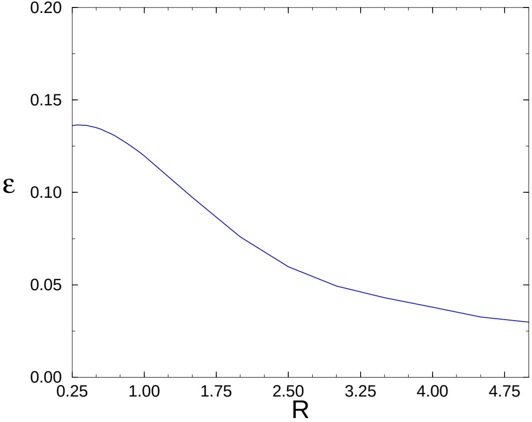
$\mu^2 = 0$ at tree but becomes < 0 at one loop non-susy vacuum

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

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



$R \to 0\ :\ \varepsilon(R) \simeq 0.14$ 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

Quartic coupling $\Rrightarrow$ mass prediction:

- tree level : $M_H = M_Z$

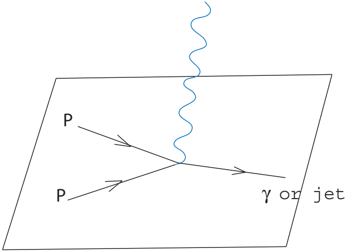
- low-energy SM radiative corrections (from top quark) : $M_H \sim 120$ GeV

Casas-Espinosa-Quiros-Riotto, Carena-Espinosa-Quiros-Wagner '95

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

Also M_s or $1/R \sim$ a few or several TeV

Gravitational radiation in the bulk $\Rightarrow$ missing energy



Angular distribution $\Rightarrow$ spin of the graviton

present LHC bounds:

$M_* \gtrsim 2.5 - 4$ TeV

Collider bounds on $R_\perp$ in mm			
	$n=2$	$n=4$	$n=6$
LEP 2	4.8×10^{-1}	1.9×10^{-8}	6.8×10^{-11}
Tevatron	5.5×10^{-1}	1.4×10^{-8}	4.1×10^{-11}
LHC	4.5×10^{-3}	5.6×10^{-10}	2.7×10^{-12}

Other accelerator signatures: 3 different scales

- string physics

  Massive string vibrations $\Rightarrow$ 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

- Large TeV dimensions seen by SM gauge interactions

  $\Rightarrow$ KK resonances of SM gauge bosons I.A. '90

  $$M_k^2 = M_0^2 + \frac{k^2}{R^2} \ ; \ k = \pm 1, \pm 2, \ldots \quad R = V_{\|}^{1/d_{\|}} \quad ; \quad g^2 = 1/(V_{\|} M_s^{d_{\|}})$$

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

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

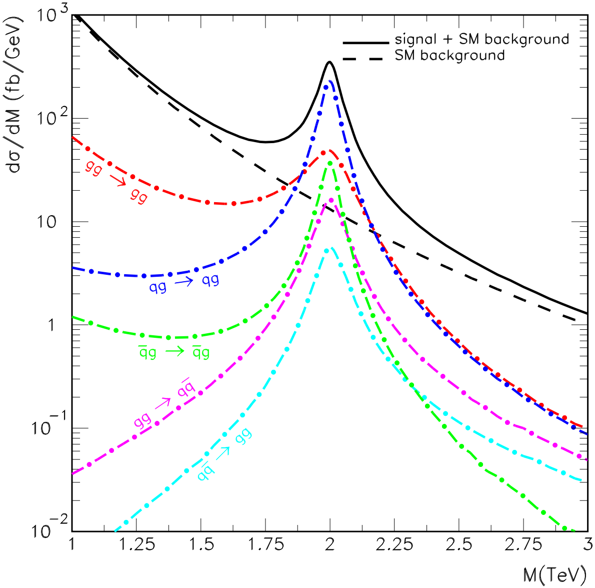
  masses suppressed by a loop factor from M_s [27]

Universal deviation from Standard Model in dijet distribution

$M_s = 2$ TeV

Width $=$ 15-150 GeV

Anchordoqui-Goldberg-Lüst-Nawata-Taylor-Stieberger '08



present LHC limits: $M_s \gtrsim 4.5$ TeV

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

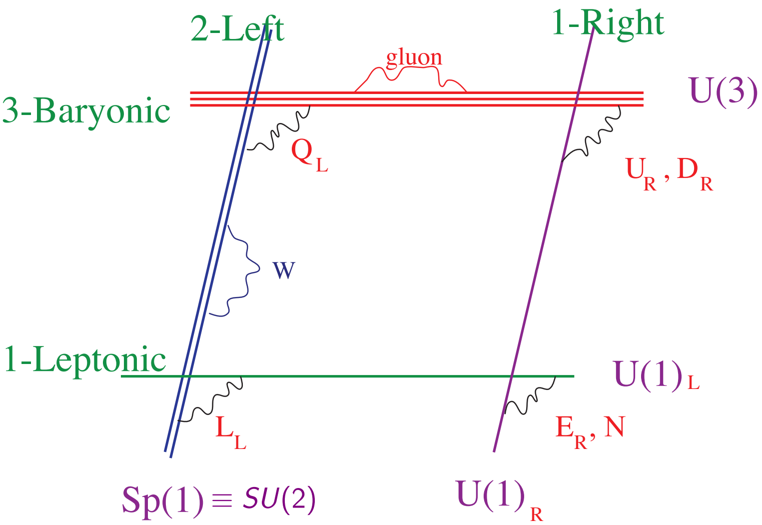
- 4d anomalous $U(1)$'s: $M_A \simeq g_A M_s$

- 4d non-anomalous $U(1)$'s: (but masses related to 6d anomalies)

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

or massless in the absence of such anomalies

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



$U(1)^3$: hypercharge + B, L global

- 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: $\frac{\langle H \rangle^2}{M_s} LL$

  $\sim$ 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 $Z'' \simeq B - L$ [36]

More general framework: large number of species

N particle species $\Rightarrow$ lower quantum gravity scale : $\quad M_*^2 = M_p^2/N$

Dvali '07, Dvali, Redi, Brustein, Veneziano, Gomez, Lüst '07-'10

derivation from: black hole evaporation or quantum information storage

$M_* \simeq 1$ TeV $\Rightarrow N \sim 10^{32}$ particle species !

2 ways to realize it lowering the string scale

1. Large extra dimensions SM on D-branes [20]

   $N = R_\perp^n\, l_s^n$: number of KK modes up to energies of order $M_* \simeq M_s$

2. Effective number of string modes contributing to the BH bound

   $N = \dfrac{1}{g_s^2}$ with $g_s \simeq 10^{-16}$ SM on NS5-branes

I.A.-Pioline '99, I.A.-Dimopoulos-Giveon '01

Gauge/Gravity duality $\Rightarrow$ toy 5d bulk model

Gravity background : near horizon geometry (holography) Maldacena '98

Analogy from D3-branes : AdS_5

NS-5 branes : $(\mathcal{M}_6 \underset{\uparrow}{\otimes} \mathbb{R}_+)$

linear dilaton background in 5d flat string-frame metric $\Phi = -\alpha|y|$

Aharony-Berkooz-Kutasov-Seiberg '98

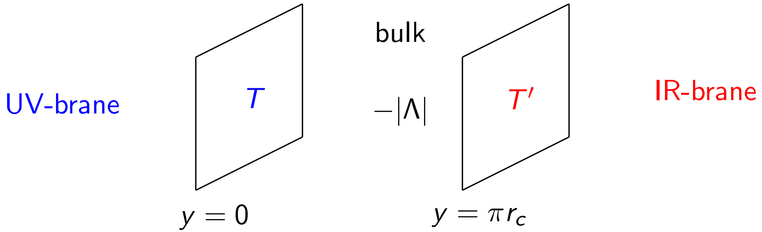
"cut" the space of the extra dimension $\Rightarrow$ gravity on the brane

$$S_{bulk} = \int d^4x \int_0^{r_c} dy \sqrt{-g}\, e^{-\Phi} \left(M_5^3 R + M_5^3 (\nabla\Phi)^2 - \Lambda \right)$$

$$S_{vis(hid)} = \int d^4x \sqrt{-g} \left(e^{-\Phi} \right) \left(L_{SM(hid)} - T_{vis(hid)} \right)$$

Tuning conditions: $T_{vis} = -T_{hid} \leftrightarrow \Lambda < 0$ [33]

spacetime = slice of AdS_5 : $\quad ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2 \quad k^2 \sim \Lambda/M_5^3$



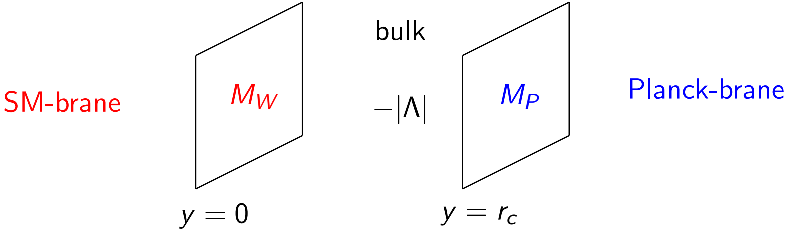
- exponential hierarchy: $M_W = M_P e^{-2kr_c} \quad M_P^2 \sim M_5^3/k \quad M_5 \sim M_{GUT}$
- 4d gravity localized on the UV-brane, but KK gravitons on the IR

$m_n = c_n\, k\, e^{-2kr_c} \sim \text{TeV} \qquad c_n \simeq (n + 1/4)$ for large n

$\Rightarrow$ spin-2 TeV resonances in di-lepton or di-jet channels dilaton $\Phi = -\alpha|y|$ and flat metric $\Rightarrow$

$$g_s^2 = e^{-\alpha|y|} \; ; \; ds^2 = e^{\frac{2}{3}\alpha|y|}\left(\eta_{\mu\nu}dx^\mu dx^\nu + dy^2\right) \leftarrow \text{Einstein frame}$$

$z \sim e^{\alpha y/3} \Rightarrow$ polynomial warp factor + log varying dilaton



- exponential hierarchy: $g_s^2 = e^{-\alpha|y|}$ $\quad M_P^2 \sim \frac{M_5^3}{\alpha} e^{\alpha r_c}$ $\quad \alpha \equiv k_{RS}$
- 4d graviton flat, KK gravitons localized near SM

LST KK graviton phenomenology

- KK spectrum : $m_n^2 = \left(\frac{n\pi}{r_c}\right)^2 + \frac{\alpha^2}{4}$; $n = 1, 2, \ldots$

  $\Rightarrow$ mass gap + dense KK modes $\alpha \sim 1$ TeV $r_c^{-1} \sim 30$ GeV

- couplings : $\frac{1}{\Lambda_n} \sim \frac{1}{(\alpha r_c) M_5}$

  $\Rightarrow$ extra suppression by a factor $(\alpha r_c) \simeq 30$

- width : $1/(\alpha r_c)^2$ suppression ~ 1 GeV

  $\Rightarrow$ narrow resonant peaks in di-lepton or di-jet channels

- extrapolates between RS and flat extra dims ($n = 1$)

  $\Rightarrow$ distinct experimental signals

Radion stabilization

Cox-Gherghetta '12

Similar to RS using the dilaton as the Goldeberger-Wise scalar

add dilaton boundary potentials $\Rightarrow$

radion stabilization with the desired hierarchy

Radion phenomenology different from RS:

- mass spectrum: similar to the graviton KK modes

  with possible lower parametrically mass gap
- new radion couplings to SM fields besides to the trace of $T_{\mu\nu}$
- larger coupling to the radion 0-mode relative to KK excitations
- Higgs-radion mixing $\Rightarrow$

  branching fraction to $\gamma\gamma$ can be significantly enhanced

Conclusions

- Possible discovery of the Higgs scalar at the LHC: big step forward
- 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?
- Good chance that next phase of LHC run will provide the answer