Strings and extra dimensions: Mass hierarchies and experimental signatures

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- High string scale, SUSY and 125 GeV Higgs
- Low scale strings and extra dimensions (flat and warped)
- Extra $U(1)$'s

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

Standard picture: low energy supersymmetry

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

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

Higgs and SUSY searches

Higgs-like excess in the light mass region :

- consistent with expectation from precision tests of the SM
- favors perturbative physics (technicolor is falsified again)

If its mass is confirmed around 125 GeV :

- supersymmetry becomes 'severely' fine-tuned, in its minimal version
- but too 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

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

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

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 $\times \Lambda^2$ [7]

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 $\Rightarrow R_{\|} \simeq l_{\rm string}$; $R_\perp$ 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 $\Rightarrow R_\perp^n = 10^{32}\ l_s^n$ [20]

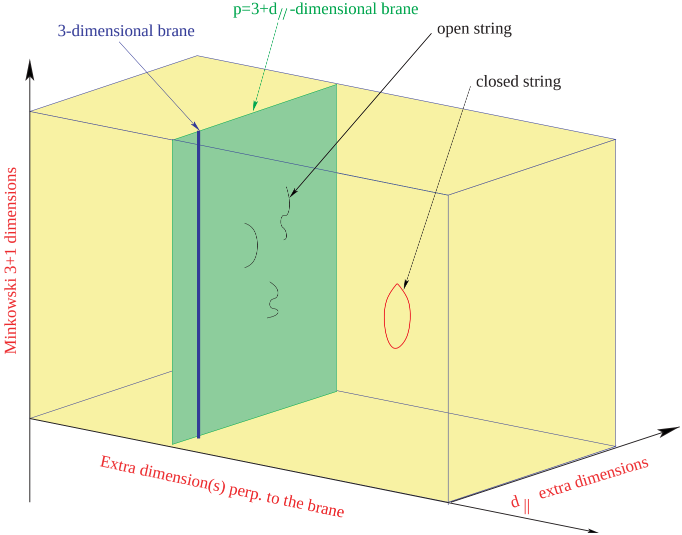
$R_\perp \sim .1 - 10^{-13}$ mm for $n = 2-6$

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

Braneworld

2 types of compact extra dimensions:

- parallel ($d_{\parallel}$): $\lesssim 10^{-16}$ cm (TeV)
- transverse ($\perp$): $\lesssim 0.1$ mm (meV)



Origin of EW symmetry breaking?

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

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

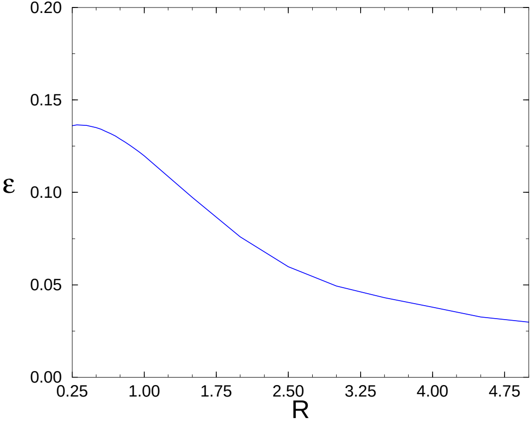
$\mu^2 = 0$ at tree but becomes < 0 at one loop — non-susy vacuum

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

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



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

Quartic coupling $\Rrightarrow$ mass prediction:

- tree level : $M_H = M_Z$

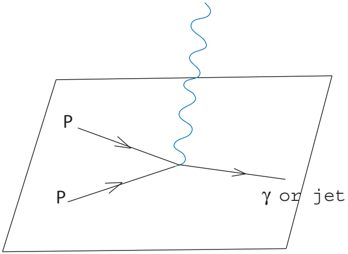
- low-energy SM radiative corrections (from top quark) : $M_H \sim 120$ GeV

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

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

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

Gravitational radiation in the bulk ⇒ missing energy



Angular distribution ⇒ spin of the graviton

present LHC bounds:

$M_* \gtrsim 2 - 3.5$ 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}

Micro-black hole production?

String-size black hole energy threshold : $M_{\rm BH} \simeq M_s/g_s^2$

Horowitz-Polchinski '96, Meade-Randall '07

weakly coupled theory $\Rightarrow$ strong gravity effects occur much above M_s, M_*

$g_s \sim 0.1$ (gauge coupling) $\quad\Rightarrow\quad M_{\rm BH} \sim 100 M_s$

Comparison with Regge excitations : $M_j = M_s\sqrt{j} \;\Rightarrow$

production of $j \sim 1/g_s^4 \sim 10^4$ string states before reach $M_{\rm BH}$

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 [14]

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

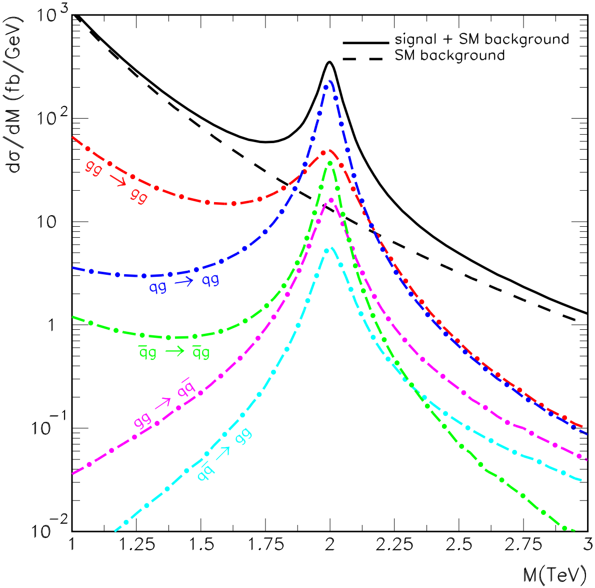
  $$M_k^2 = M_0^2 + \frac{k^2}{R^2} \;;\; k = \pm 1, \pm 2, \dots \quad R = V_\parallel^{1/d_\parallel} \quad ; \quad g^2 = 1/(V_\parallel M_s^{d_\parallel})$$

  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 [16]

Universal deviation from Standard Model in dijet distribution



$M_s = 2$ TeV

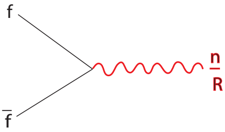
Width = 15-150 GeV

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

present LHC limits: $M_s \gtrsim 4$ TeV

Localized fermions (on 3-brane intersections) [12]

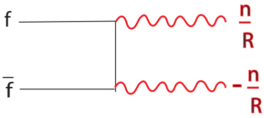
$\Rightarrow$ single production of KK modes I.A.-Benakli '94



- strong bounds indirect effects
- new resonances but at most $n = 1$

Otherwise KK momentum conservation

$\Rightarrow$ pair production of KK modes (universal dims)

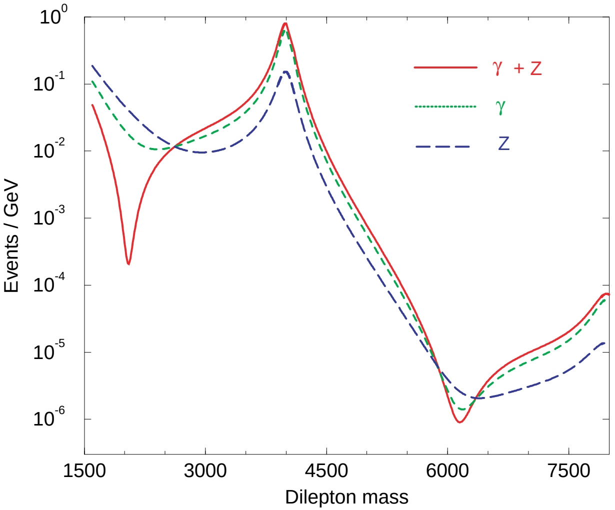


- weak bounds
- no resonances
- lightest KK stable : dark matter candidate

Servant-Tait '02

$R^{-1} = 4$ TeV

I.A.-Benakli-Quiros '94, '99



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

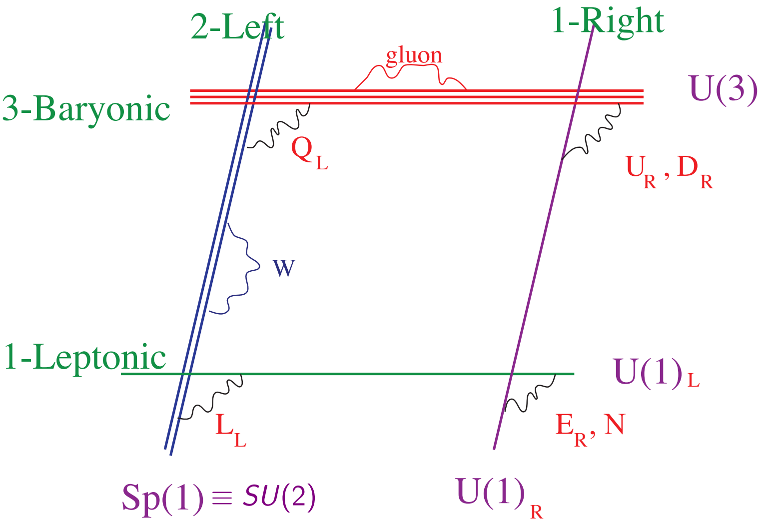
- 4d anomalous $U(1)$'s: $M_A \simeq g_A M_s$

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

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

or massless in the absence of such anomalies

Standard Model on D-branes



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

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 $\Rrightarrow \frac{1}{M_s}LLHH \to$ 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 $Z'' \simeq B - L$

High string scale

AAGHLT+Vlcek to appear

- $Z' \simeq B$ anomalous and superheavy
- $Z'' \simeq B - L$ 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
- present LHC limits: $m_{Z''} \gtrsim 2.5$ TeV scale
- interesting LHC phenomenology and cosmology [25]

More general framework: large number of species

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

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 [5]

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

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

   $N = \frac{1}{g_s^2}$ 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

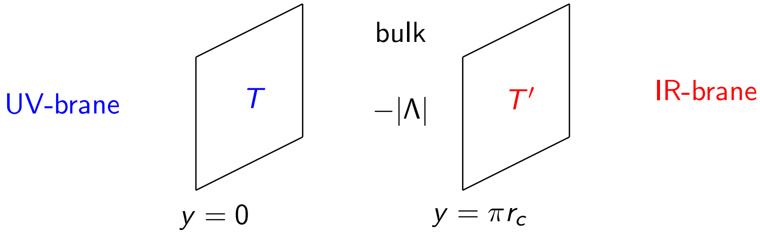
$$S_{bulk} = \int d^4x \int_0^{r_c} dy \sqrt{-g}\, e^{-\Phi} \left(M_5^3 R + M_5^3 (\nabla\Phi)^2 - \Lambda\right)$$

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

Tuning conditions: $T_{vis} = -T_{hid} \leftrightarrow \Lambda < 0$ [23]

Randal Sundrum models

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

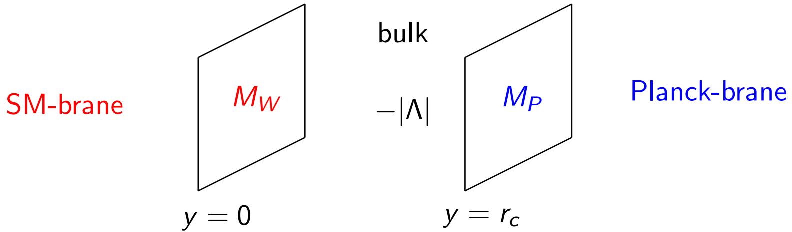
$m_n = c_n\, k\, e^{-2kr_c} \sim \text{TeV} \qquad c_n \simeq (n + 1/4)$ for large n

$\Rightarrow$ spin-2 TeV resonances in di-lepton or di-jet channels

Linear dilaton background IA-Arvanitaki-Dimopoulos-Giveon '11

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

$z \sim e^{\alpha y/3} \Rightarrow$ 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 $\quad \alpha \sim 1$ TeV $\quad r_c^{-1} \sim 30$ 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

Conclusions

- Possible discovery of the Higgs scalar at the LHC: big step forward
- Precise measurement of its couplings is of primary importance
- hint of Nature's answer to the mass hierarchy question

  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