

# String mass hierarchies and experimental predictions

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- High string scale, SUSY and 125 GeV Higgs
- Low scale strings and extra dimensions
- 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 % - %<sub>00</sub> 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

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 $\Lambda \sim \text{TeV}$

- 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

$\Lambda \sim \text{a few TeV}$  and  $m_H^2 = \text{a loop factor} \times \Lambda^2$  [6]

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

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

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

$$M_S \sim 1 \text{ TeV} \Rightarrow R_{\perp}^n = 10^{32} l_S^n \quad \text{small } M_S/M_P : \text{extra-large } R_{\perp}$$

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

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:  $\lambda = \frac{1}{8}(g_2^2 + g'^2)$

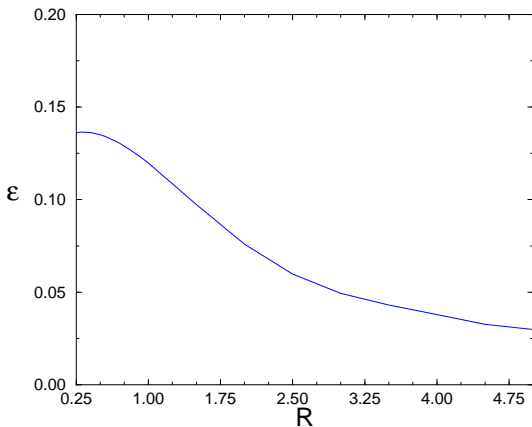
D-terms

$\mu^2 = -g^2 \epsilon^2 M_5^2 \leftarrow$  effective UV cutoff

$$\epsilon^2(R) = \frac{R^3}{2\pi^2} \int_0^\infty dl l^{3/2} \frac{\theta_2^4}{16l^4 \eta^{12}} \left( il + \frac{1}{2} \right) \sum_n n^2 e^{-2\pi n^2 R^2 l}$$

Diagrammatic annotations for the integral:

- UV  $\swarrow$  (blue arrow pointing to the upper limit  $\infty$ )
- IR  $\nearrow$  (red arrow pointing to the lower limit  $0$ )
- $e^{-\pi l}$   $\nearrow$  (blue arrow pointing to the exponential term)
- $1$   $\swarrow$  (red arrow pointing to the constant term  $\frac{1}{2}$ )



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

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

Higgs scalar = component of a higher dimensional gauge field

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

Quartic coupling  $\Rightarrow$  mass prediction:

- tree level :  $M_H = M_Z$

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

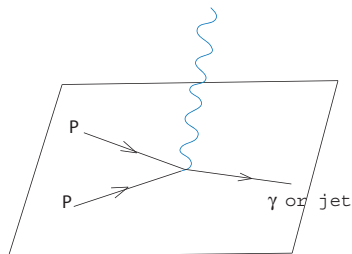
Casas-Espinosa-Quiros-Riotto, Carena-Espinosa-Quiros-Wagner '95

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

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



# Gravitational radiation in the bulk $\Rightarrow$ missing energy



Angular distribution  $\Rightarrow$  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	$4.8 \times 10^{-1}$	$1.9 \times 10^{-8}$	$6.8 \times 10^{-11}$
Tevatron	$5.5 \times 10^{-1}$	$1.4 \times 10^{-8}$	$4.1 \times 10^{-11}$
LHC	$4.5 \times 10^{-3}$	$5.6 \times 10^{-10}$	$2.7 \times 10^{-12}$

# Micro-black hole production?

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

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)  $\Rightarrow M_{\text{BH}} \sim 100M_s$

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  $M_{\text{BH}}$

## 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

$\Rightarrow$  KK resonances of SM gauge bosons

I.A. '90

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

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

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

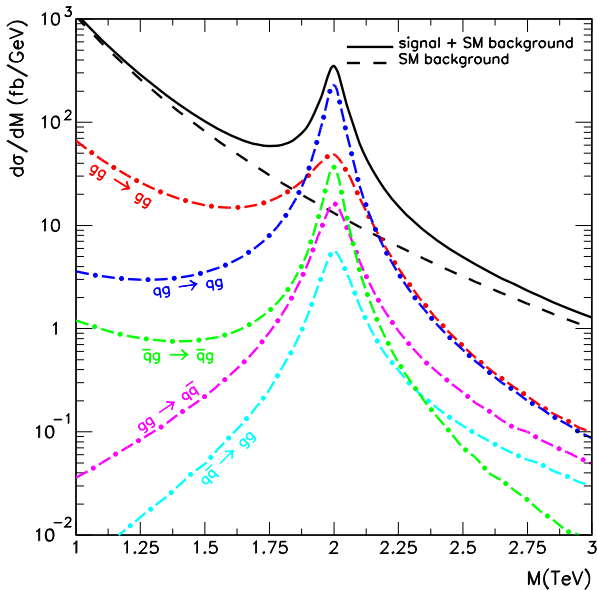
masses suppressed by a loop factor from  $M_s$  [13]

**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

# 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

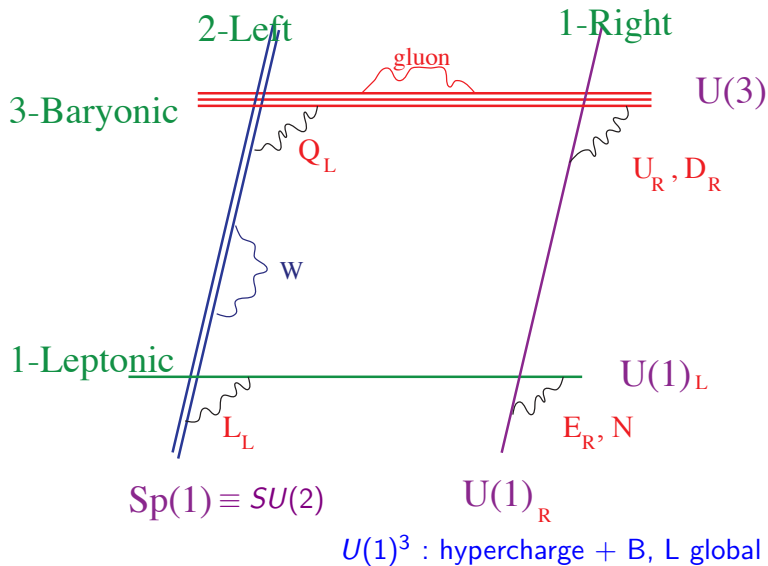
- 4d anomalous  $U(1)$ 's:  $M_A \simeq g_A M_s$

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

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

or massless in the absence of such anomalies

# Standard Model on D-branes




- $B$  and  $L$  become massive due to anomalies

Green-Schwarz terms

- the global symmetries remain in perturbation

- Baryon number  $\Rightarrow$  proton stability

- Lepton number  $\Rightarrow$  protect small neutrino masses

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


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

with possible leptophobic couplings leading to CDF-type  $W_{jj}$  events

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

- $Z' \simeq B$  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



- Rotation of  $U(1)$ 's from the string to low energy basis  $Y, Y', Y''$ : completely fixed in terms of the couplings
  - Decoupling of anomalous  $Y'$
  - $Y''$  linear combination of  $Y$  (or  $U(1)_R$ ) and  $B - L$  (mostly)
- LHC14 discovery potential:  $M_{Z''}$  up to  $\sim 5$  TeV (in dijets)

Recent cosmological observations indicate an extra relativistic component dark radiation parametrized by an effective neutrino number close to 4

→ use the 3  $\nu_R$ 's interacting with SM fermions via  $Z''$

data: their decoupling during the quark-hadron transition

- absence of chemical potential  $\Rightarrow 3.6 < M_{Z''} < 4.8$  TeV
- thermal equilibrium  $\Rightarrow 5.4 < M_{Z''} < 6$  TeV [23]

# 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

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

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 :  $(\mathcal{M}_6 \otimes \mathbb{R}_+)$

$\uparrow$   
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

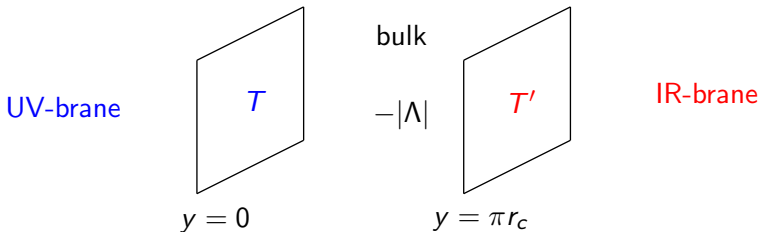
$$S_{bulk} = \int d^4x \int_0^{r_c} dy \sqrt{-g} e^{-\Phi} (M_5^3 R + M_5^3 (\nabla\Phi)^2 - \Lambda)$$

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

Tuning conditions:  $T_{vis} = -T_{hid} \leftrightarrow \Lambda < 0$  [21]

# Randal Sundrum models

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



- exponential hierarchy:  $M_W = M_P e^{-2kr_c}$   $M_P^2 \sim M_5^3/k$   $M_5 \sim M_{GUT}$

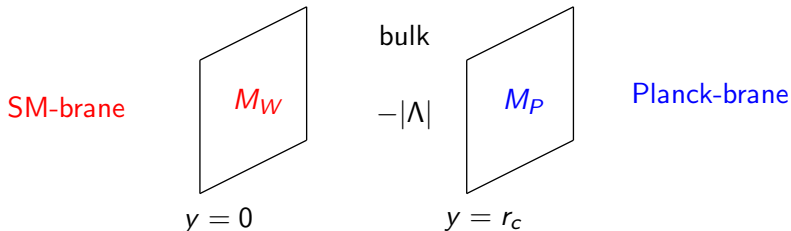
- 4d gravity localized on the UV-brane, but KK gravitons on the IR

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

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

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

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



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

# LST KK graviton phenomenology

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

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

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

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

- width :  $1/(\alpha r_c)^2$  suppression  $\sim 1 \text{ GeV}$

⇒ narrow resonant peaks in di-lepton or di-jet channels

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

⇒ 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