Mass hierarchies in string theory and experimental predictions

I. Antoniadis

CERN

SCALARS 2011 – Warsaw, 26-29 August 2011

1. Motivations and mass hierarchy
2. Strings, branes and extra dimensions (flat and warped)
3. Infinitesimal string coupling and linear dilaton background
4. Main accelerator signatures and nature of the EWSB scalar

BSM physics: driven by mass hierarchy problem

EW scale: very sensitive to high energy physics $\sim$ UV cutoff Λ

why gravity is so weak compared to the other interactions? $\Lambda = M_P$

Possible answer (alternative to supersymmetry): Low UV cutoff $\Lambda \sim$ TeV

- low scale gravity $\Rightarrow$ large extra dimensions, warped dimensions

- 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

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 $\qquad$ $6 - n$ parallel

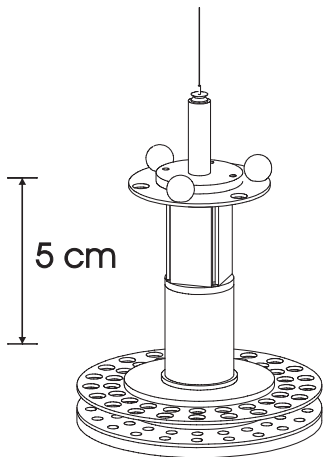calculability $\Rightarrow R_\parallel \simeq l_{\text{string}}$; $R_\perp$ arbitrary

$M_P^2 \simeq \frac{1}{g_s^2} M_s^{2+n} R_\perp^n$ $\qquad\qquad$ $g_s = \alpha$: 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 $\Rightarrow R_\perp^n = 10^{32} \, l_s^n$ [16]

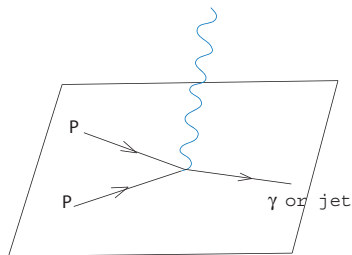$$R_\perp \sim .1 - 10^{-13} \text{ mm for } n = 2 - 6$$

distances $< R_\perp$: gravity $(4+n)$-dim $\rightarrow$ strong at 10^{-16} cm [5]

5 cm

$R_\perp \lesssim 45~\mu$m at 95% CL

• dark-energy length scale $\approx 85\mu$m

Gravitational radiation in the bulk $\Rightarrow$ missing energy

Angular distribution $\Rightarrow$ spin of the graviton

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}

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

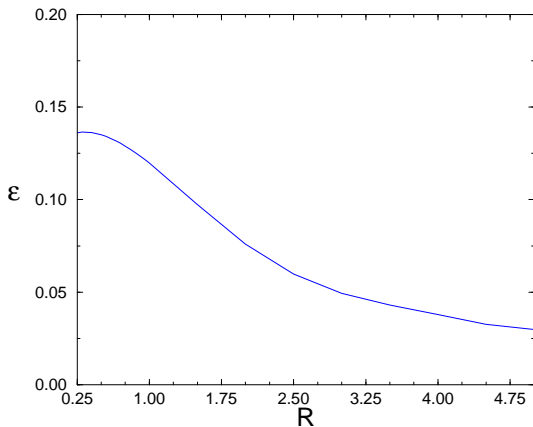$\Rightarrow$ tree-level V same as susy: $\lambda = \frac{1}{8}(g^2 + g'^2)$ D-terms

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

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

UV $\searrow$ $\nearrow e^{-\pi l}$

IR $\nearrow$ $\searrow 1$

$R \to 0 \ : \ \varepsilon(R) \simeq 0.14$ 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: $M_s \to 1/R$

Brout-Englert-Higgs = component of a higher dim gauge field

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

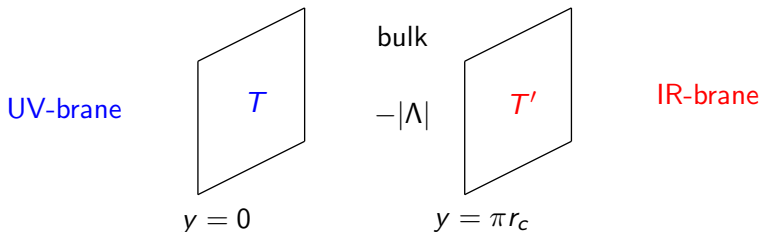Quartic coupling $\Rightarrow$ mass prediction:

- tree level : $M_H = M_Z$

- low-energy SM radiative corrections top quark sector : $M_H \sim 120$ GeV

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

Randal Sundrum models

spacetime = slice of AdS$_5$: $\quad ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2 \quad k^2 \sim \Lambda/M_5^3$

bulk

UV-brane $\qquad T \qquad -|\Lambda| \qquad T' \qquad$ IR-brane

$y = 0 \qquad\qquad y = \pi r_c$

- 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

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

  $\Rightarrow$ spin-2 TeV resonances in di-lepton or di-jet channels [18] [19]

- weakly coupled for $m_n < M_5\, e^{-2kr_c}$ $\quad \Rightarrow k < M_5$

- viable models: SM gauge bosons in the bulk

  EWSB sector on the IR-brane

- AdS/CFT duals to strongly coupled 4d field theories

  composite models, technicolor-type $\quad g_{YM} = M_5/k > 1$

Other accelerator signatures

- Large TeV dimensions   seen by SM gauge interactions

  ⇒ KK resonances of SM gauge bosons   I.A. '90

  $$M_n^2 = M_0^2 + \frac{n^2}{R^2} \quad ; \quad n = \pm 1, \pm 2, \ldots$$

- string physics and possible strong gravity effects

  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

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

  production of micro-black holes?

  Giddings-Thomas, Dimopoulos-Landsberg '01

Black hole production

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

Horowitz-Polchinski '96, Meade-Randall '07

- string size black hole: $r_H \sim l_s = M_s^{-1}$

- black hole mass: $M_{\mathrm{BH}} \sim r_H^{d-3}/G_N$ $G_N \sim l_s^{d-2} g_s^2$

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

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

Comparison with Regge excitations : $M_n = M_s \sqrt{n}$ $\Rightarrow$

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

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)

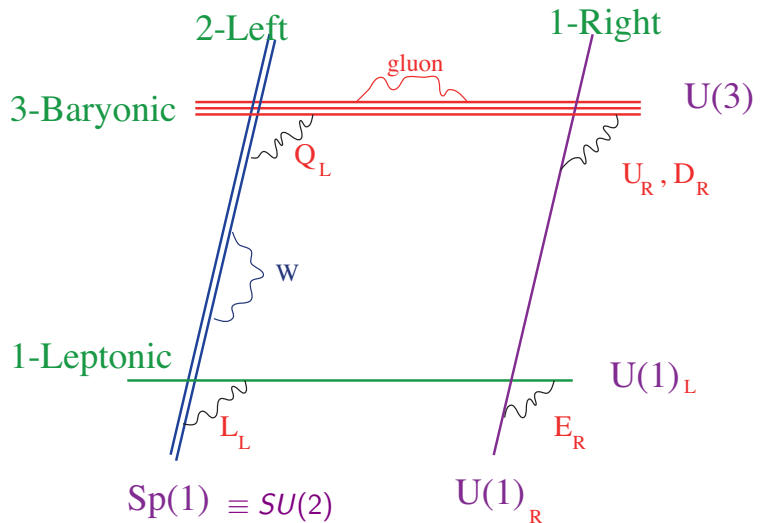Baryon and Lepton number, or PQ symmetry

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 $\Rightarrow M_{NA} \geq M_A$

2-Left

1-Right

3-Baryonic $\qquad$ gluon $\qquad$ U(3)

Q_L

U_R, D_R

w

1-Leptonic $\qquad$ U(1)$_L$

L_L

E_R

Sp(1) $\equiv SU(2)$ U(1)$_R$

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

global symmetries

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

  $\sim$ GeV

- $B, L \Rightarrow$ extra Z's   (B lighter than 4d anomaly fee $B - L$)

  with possible leptophobic couplings leading to CDF-type Wjj events [3]

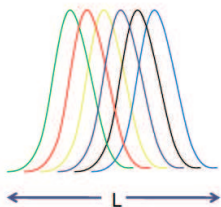 Anchordoqui-I.A.-Goldberg-Huang-Lüst-Taylor '11

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

Pixel of size L containing N species storing information:

localization energy $E \gtrsim N/L \rightarrow$

Schwarzschild radius $R_s = N/(LM_p^2)$

no collapse to a black hole : $L \gtrsim R_s \Rightarrow L \gtrsim \sqrt{N}/M_p = 1/M_*$

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

2 ways to realize $N = 10^{32}$ lowering the string scale

① Large volume compactifications   SM on D-branes [3]

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

② $N \sim$ effective number of string modes contributing to the BH bound

Dvali-Lüst '09, Dvali-Gomez '10

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

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

in this case gravity does NOT become strong at M_s

Both ways are compatible with the general string relation:

$$M_P^2 = \frac{1}{g_s^2} \, V_6 \, M_s^8 \qquad V_6 : \text{internal } 6d \text{ compactification volume}$$

Gauge/Gravity duality ⇒ toy 5d bulk model

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

Analogy from D3-branes : AdS_5

NS-5 branes : $(\mathcal{M}_6 \otimes \mathbb{R}_+)$
↑
linear dilaton background in 5d flat string-frame metric $\Phi = -\alpha|y|$

Aharony-Berkooz-Kutasov-Seiberg '98

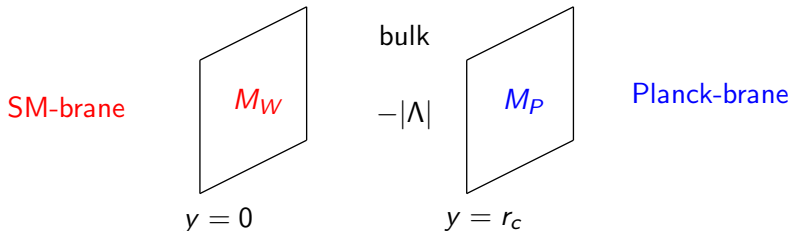"cut" the space of the extra dimension ⇒ gravity on the brane

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

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

Tuning conditions: $T_{vis} = -T_{hid} \leftrightarrow \Lambda < 0$ [9]

Linear dilaton background

$$g_s^2 = e^{-\alpha|y|} \; ; \; ds^2 = e^{\frac{2}{3}\alpha|y|}\left(\eta_{\mu\nu}dx^\mu dx^\nu + dy^2\right) \leftarrow \text{Einstein frame}_{[9]}$$

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

SM-brane M_W bulk $-|\Lambda|$ M_P Planck-brane

$y = 0$ $y = r_c$

- exponential hierarchy: $g_s^2 = e^{-\alpha|y|}$ $M_P^2 \sim \frac{M_5^3}{\alpha} e^{\alpha r_c}$ $\alpha \equiv k_{RS}$

- 4d graviton flat, KK gravitons localized near SM

LST KK graviton phenomenology

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

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

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

  $\Rightarrow$ 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

Mass hierarchy $\Rightarrow$ testing strings at the TeV ?

- Well motivated theoretical framework

  with many testable experimental predictions

  new resonances, missing energy

- Several realizations with different signatures

  flat large extra dimensions, exp warped metrics,

  tiny string coupling and linear dilaton background

- Stimulus for micro-gravity experiments and accelerator searches