Mass hierarchies in string theory, holography and experimental signatures

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1. Motivations and mass hierarchy
2. Strings, branes and extra dimensions (flat and warped)
3. Gravity scale and number of species
4. Infinitesimal string coupling and linear dilaton background
5. Main accelerator signatures

BSM physics: driven by mass hierarchy problem

Higgs mass: very sensitive to high energy physics $m_H \sim$ 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 $6-n$ 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}

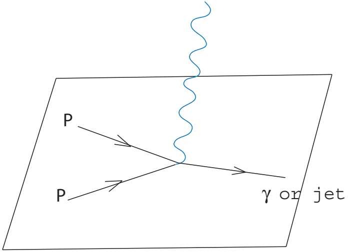
small M_s/M_P : extra-large $R_\perp$

$M_s \sim 1$ TeV $\Rightarrow R_\perp^n = 10^{32}\, l_s^n$ [11]

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

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

Gravitational radiation in the bulk ⇒ missing energy

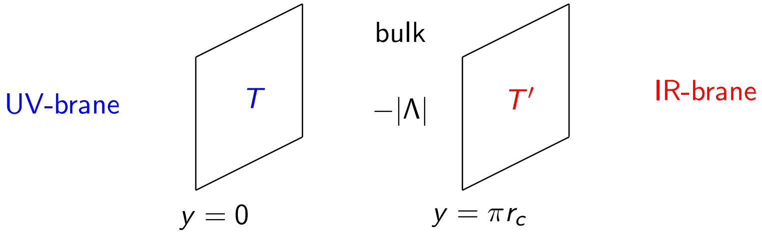


Angular distribution ⇒ spin of the graviton

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}

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

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

$\Rightarrow$ spin-2 TeV resonances in di-lepton or di-jet channels [16] [17]

Other accelerator signatures

- Large TeV dimensions seen by SM gauge interactions

  $\Rightarrow$ 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 $\Rightarrow$ 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

  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 : $M_{\rm BH} \simeq M_s/g_s^2$

Horowitz-Polchinski '96, Meade-Randall '07

- string size black hole: $r_H \sim l_s = M_s^{-1}$
- black hole mass: $M_{\rm BH} \sim r_H^{d-3}/G_N$ $\qquad G_N \sim l_s^{d-2} g_s^2$

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

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

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 $M_{\rm BH}$ [3]

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

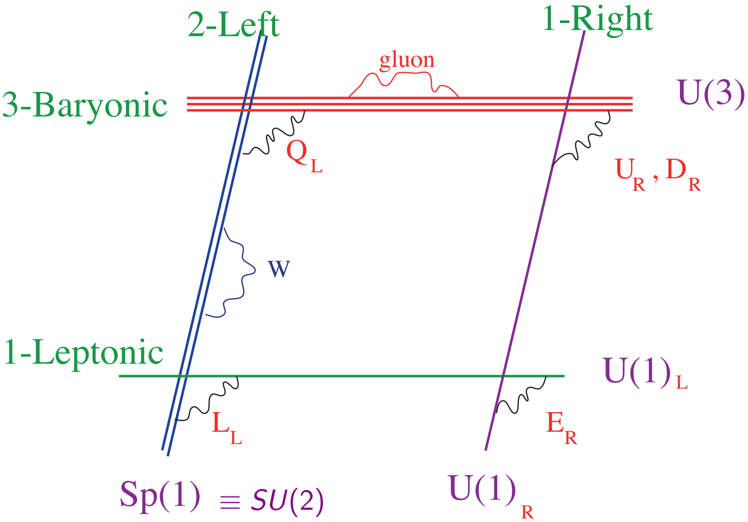
Two kinds of massive $U(1)$'s: I.A.-Kiritsis-Rizos '02

- 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 $\Rightarrow M_{NA} \geq M_A$

Standard Model on D-branes



$U(1)^3$: 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

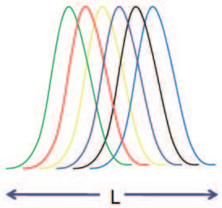
More general framework: large number of species

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

   $N_s = \frac{1}{g_s^2}$ 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:

$$M_P^2 = \frac{1}{g_s^2} V_6 \, M_s^8$$

V_6 : internal $6d$ compactification volume puzzle as $g_s \to 0$:

- M_* remains finite $\Rightarrow$ Quantum Gravity effects in a free theory

  $M_*^2 = M_p^2/N \simeq M_s^2/(g_s^2 N) \sim M_s^2$ since $N \simeq 1/g_s^2$

- forward 4pt amplitude does not decouple

  e.g. $\sum_{\text{string states } X} |q\bar{q} \to X|^2 \sim g_s^2 \times N \sim \mathcal{O}(1)$ at M_*

solution: log corrections $N(M_*) \sim 1/(g_s \ln g_s)^2 \quad M_* \sim M_s |\ln g_s|$

string density of states: $N(M_*) \sim \left(\frac{M_*}{M_s}\right)^{-d} e^{\beta M_*/M_s}$

$d = 4\,;\ \beta = 2\sqrt{2}\pi$ for closed superstrings

$M_*^2 = \frac{M_s^2}{g_s^2 N} v_6 \leftarrow$ 6d volume in string units

$$\Rightarrow \frac{1}{g_s\sqrt{N}} = \frac{1}{\beta}\ln N - \frac{d}{\beta}\ln\ln N + \ldots$$

What is LST ? Decouple gravity from NS5-branes

Analogy from D3-branes : decouple gravity $\Rightarrow M_s \to \infty$, g_s fixed

$\to$ (conformal) Field Theory (CFT)

simplest case: 4d $\mathcal{N} = 4$ super Yang Mills $SU(N)$

parameters: number of branes N, gauge coupling g_{YM}

NS-5 branes: M_s finite, $g_s \to 0 \to$ (little) String Theory without gravity

simplest case: 6d LST (chiral IIA or non-chiral IIB)

massless sector: 6d $SU(N)$ of tensors (IIA) or vectors (IIB)

at a non-trivial fixed point

parameters: number of branes N, string scale M_s

How to study LST ? Using gauge/gravity duality

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

Analogy from D3-branes : $AdS_5 \times S^5$

parameters: AdS radius $r_{AdS} M_s$, $g_s \leftrightarrow N, g_{YM}$

supergravity validity: $r_{AdS} M_s >> 1$, $g_s << 1 \Rightarrow$ large N, $g^2_{YM} N$

$\longrightarrow$ model independent part : AdS_5

NS-5 branes : $(\mathcal{M}_6 \otimes R_+) \times SU(2) \equiv S^3$

$\uparrow$ linear dilaton background in 7d flat string-frame metric $\Phi = -\alpha|y|$

Aharony-Berkooz-Kutasov-Seiberg '98

parameters: M_s, α (or S^3 radius) $\leftrightarrow N$

sugra validity: small $\alpha \Rightarrow$ large N

compactify to $d = 4\,(\mathcal{M}_6 \to \mathcal{M}_4) \Rightarrow g_{YM} \sim$ 2d volume

$\longrightarrow$ model independent part : linear dilaton

Put gravity back **but weakly coupled**

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

Analogy from D-branes $\rightarrow$ 2 possibilities:

- flat space $\Rightarrow$ large extra dimensions AADD '98
- curved space from gravity back reaction $\Rightarrow$ slice of AdS_5

RS, H. Verlinde '99

NS-5 branes : linear dilaton on an interval $y \in [0, r_c]$

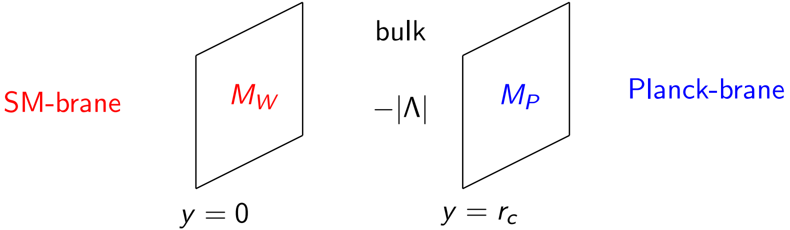
$$S_{bulk} = \int d^4x\, dy \sqrt{-g}\, e^{-\Phi} \left(M_5^3 R + M_5^3 (\nabla\Phi)^2 - \Lambda \right)$$

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

Tuning conditions: $T_{vis} = -T_{hid} \leftrightarrow \Lambda < 0$ [5]

$$g_s^2 = e^{-\alpha|y|}\ ;\ ds^2 = e^{\frac{2}{3}\alpha|y|}\left(\eta_{\mu\nu}dx^\mu dx^\nu + dy^2\right) \leftarrow \text{Einstein frame}$$ [5]

$z \sim e^{\alpha y/3} \Rightarrow$ 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

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