Physics and signatures of strings and extra dimensions

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Excited QCD 2011, Les Houches (France), 20-25 February 2011

1. Motivations and mass hierarchy
2. Strings, branes and extra dimensions
3. Gravity scale and number of species
4. 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

explicit model building is not necessary at this moment

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

$\nwarrow$ 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]

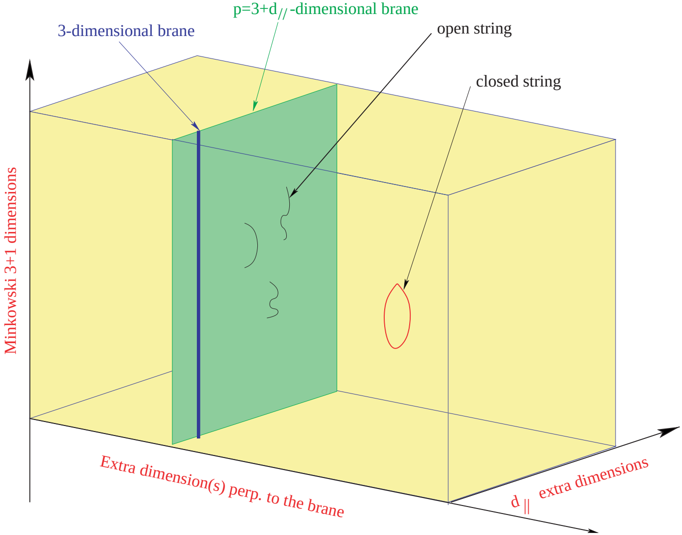
$R_\perp \sim .1 - 10^{-13}$ mm for $n = 2 - 6$ [5]

distances $< R_\perp$: gravity $(4+n)$-dim $\rightarrow$ strong at 10^{-16} cm [6]

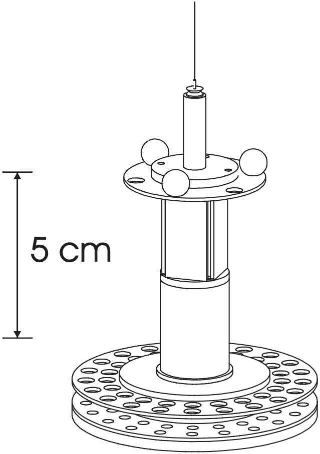
Braneworld

2 types of compact extra dimensions:

- parallel ($d_\parallel$): $\lesssim 10^{-16}$ cm (TeV) [8]
- transverse ($\perp$): $\lesssim 0.1$ mm (meV) [11]



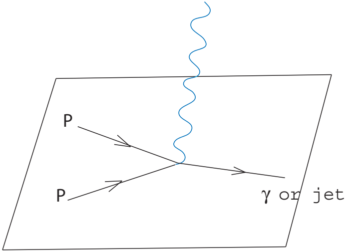
Adelberger et al. '06



$R_\perp \lesssim 45\ \mu\text{m}$ at 95% CL

- dark-energy length scale $\approx 85\mu$m [3] [??]

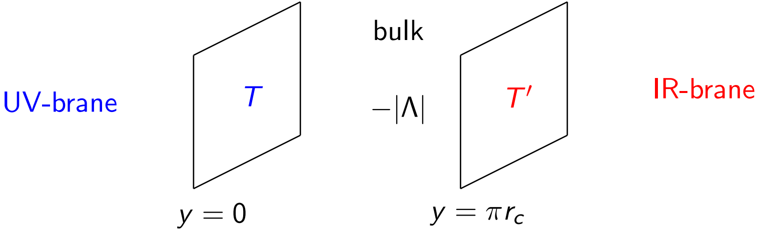
Gravitational radiation in the bulk ⇒ missing energy



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}
NLC	1.2×10^{-2}	1.2×10^{-9}	6.5×10^{-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 [18]

Other accelerator signatures

- Large TeV dimensions seen by SM gauge interactions

  ⇒ KK resonances of SM gauge bosons [4] 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 [12]

  $$M_j^2 = M_0^2 + M_s^2\, j \quad ; \quad \text{maximal spin} : j+1$$

  higher spin excitations of quarks and gluons with strong interactions

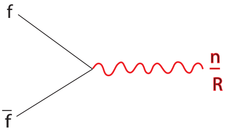
  Anchordoqui-Goldberg-Lüst-Nawata-Taylor-Stieberger '08

  production of micro-black holes? [15]

  Giddings-Thomas, Dimopoulos-Landsberg '01

Localized fermions (on 3-brane intersections) [11]

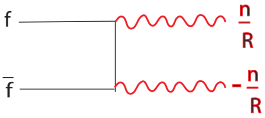
⇒ single production of KK modes I.A.-Benakli '94



- strong bounds indirect effects: $R^{-1} \gtrsim 3\,\mathrm{TeV}$
- new resonances but at most $n = 1$

Otherwise KK momentum conservation

⇒ pair production of KK modes (universal dims)

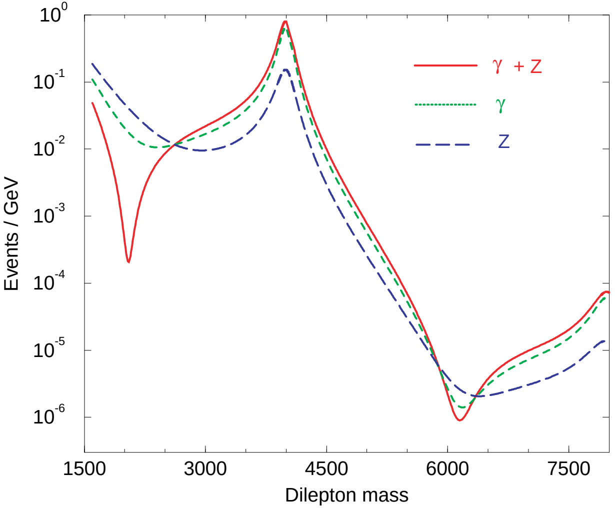


- weak bounds $R^{-1} \gtrsim$ 300-500 GeV
- no resonances
- lightest KK stable : dark matter candidate

Servant-Tait '02

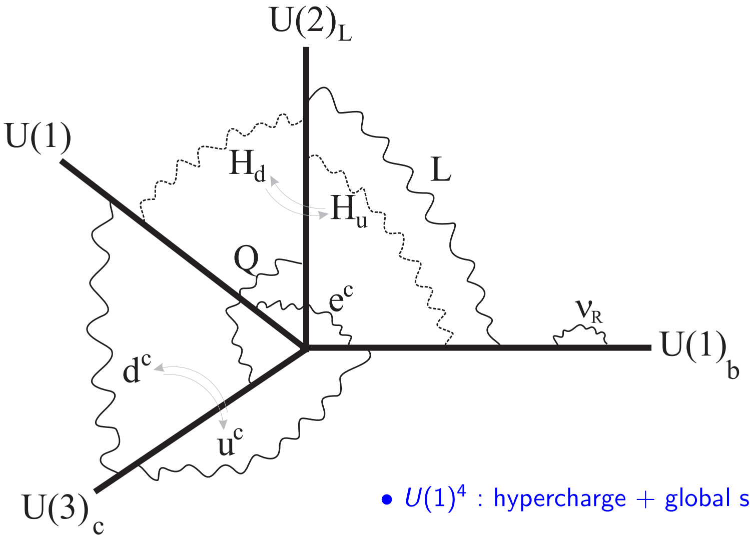
$R^{-1} = 4$ TeV

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



Standard Model on D-branes

I.A.-Kiritsis-Rizos-Tomaras '02



- $U(1)^4$: hypercharge + global symmetries
- ν_R in the bulk : small neutrino masses [9]

Massive string vibrations

indirect effects: virtual exchanges ⇒ effective interactions

e.g. four-fermion operators

Actual limits: Matter fermions on

- same set of branes ⇒ $M_s \gtrsim 500$ GeV dim-8: $\frac{g^2}{M_s^4}(\bar{\psi}\partial\psi)^2$
- brane intersections :$M_s \gtrsim 2-3$ TeV dim-6: $\frac{g^2}{M_s^2}(\bar{\psi}\psi)^2$

Cullen-Perelstein-Peskin, I.A.-Benakli-Laugier '00

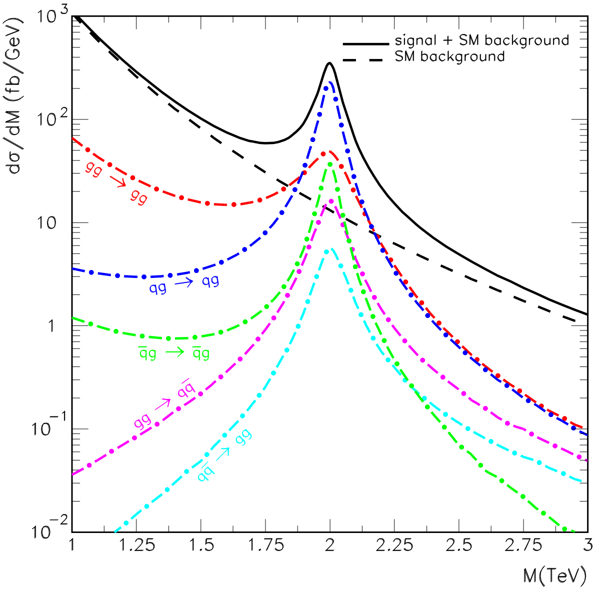
High energies ⇒ direct production: string physics

Universal deviation from Standard Model in jet distribution

$M_s = 2$ TeV

Width = 15-150 GeV

Anchordoqui-Goldberg-Lüst-Nawata-Taylor-Stieberger '08 [8]



Tree level superstring amplitudes involving at most 2 fermions and gluons:

model independent for any compactification, # of susy's, even none

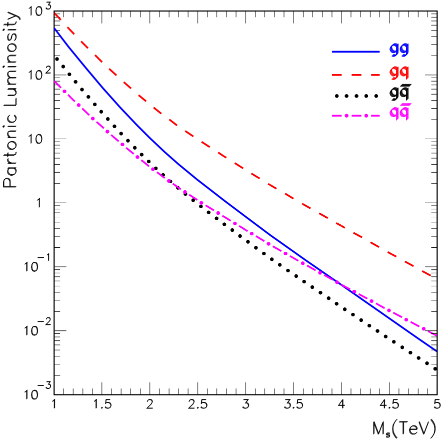
no intermediate exchange of KK, windings or graviton emmission

Universal sum over infinite exchange of string (Regge) excitations [8]

Parton luminosities in pp above TeV are dominated by *gq*, *gg*

⇒ model independent

$gq \to gq,\ gg \to gg,\ gg \to q\bar{q}$



Black hole production

String-size black hole energy threshold : $M_{\mathrm{BH}} \simeq M_s/g_s^2$ [16]

Horowitz-Polchinski '96, Meade-Randall '07

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

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

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

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_{BH} [3]

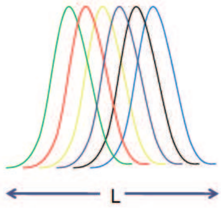
More general framework: large number of species

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

Pixel of size L containing N species storing information:



localization energy $E \gtrsim N/L \rightarrow$ [15]

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

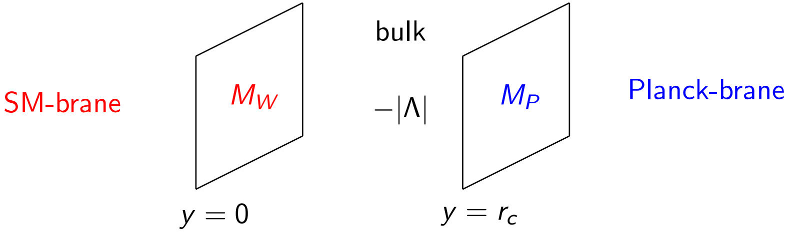
Both ways are compatible with the general string relation:

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

V_6 : internal $6d$ compactification volume

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

$g_s^2 = e^{-\alpha|y|}$; $ds^2 = e^{-\frac{2}{3}\alpha|y|}\left(\eta_{\mu\nu}dx^\mu dx^\nu + dy^2\right)$ ← Einstein frame [7]



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

  $m_n^2 = (\frac{n\pi}{r_c})^2 + \frac{\alpha^2}{4}$ $\quad \alpha \sim$ TeV $\quad r_c^{-1} \sim 30$ GeV $\quad$ mass gap + dense KK modes
- couplings: suppressed by a factor $(\alpha r_c) \simeq 30 \Rightarrow$ narrow peaks

Conclusions

Testing strings at the TeV: Physical reality or imagination?

- 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

But: - unification has to be dropped

- physics is radically changed above string scale