Models with low scale gravity and low scale strings

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1. Motivations, mass hierarchy and low UV scale proposals
2. Main experimental predictions
3. Models and phenomenology of low string scale

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, DGP localized gravity

- 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

but unification has to be probably dropped

Type I string theory $\Rightarrow$ D-brane world

- gravity: closed strings
- gauge interactions: open strings

  with their ends attached on membranes   Dirichlet branes or D-branes

Dimensions of finite size: n transverse $6-n$ parallel

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

$M_P^2 \simeq \frac{1}{\alpha^2} M_s^{2+n} R_{\perp}^n$ $\alpha = g_s$

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

small $M_s/M_P \Rightarrow$ extra-large $R_{\perp}$

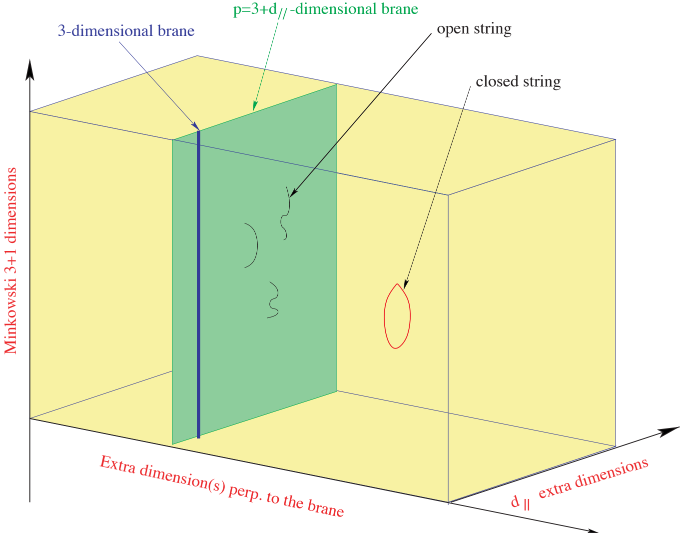
$M_s \sim 1$ TeV $\Rightarrow R_{\perp} \sim .1 - 10^{-13}$ mm $(n = 2-6)$ [5]

weak string coupling: $g_s = \alpha$ [6]

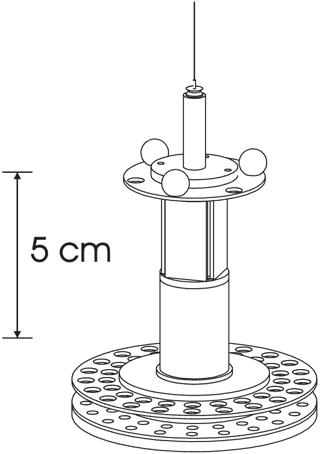
Braneworld

2 types of compact extra dimensions:

- parallel ($d_{\|}$): $\lesssim 10^{-16}$ cm (TeV) [22]
- transverse ($\perp$): $\lesssim 0.1$ mm (meV)



Adelberger et al. '06



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

- dark-energy length scale $\approx 85\mu$m [3] [18] string realization of large extra dimensions

I.A.-Arkani Hamed-Dvali-Dimopoulos '98

by 'swiss cheese' Calabi-Yau's ('large volume' compactifications) :

Balasubramanian-Berglund-Cicoli-Conlon-Quevedo-Suruliz '05-'08

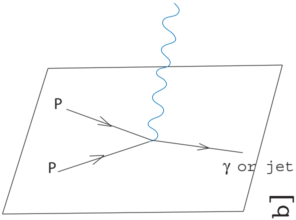
Requirements:

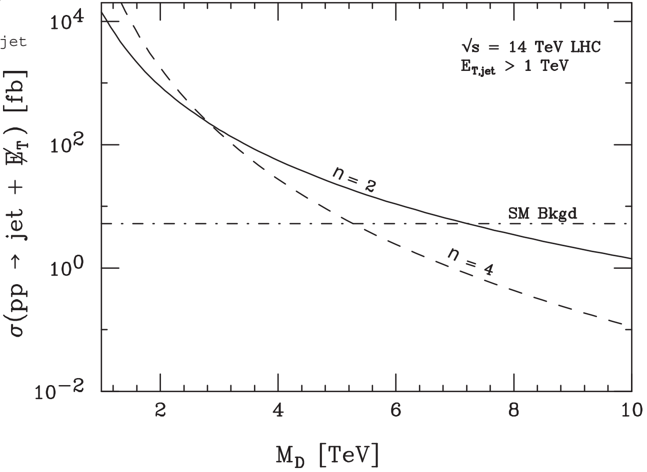
- CY with $h_{21} > h_{11} > 1$
- 3-form fluxes as KKLT
- SM on D7-branes wrapped small cycles
- at least one blow-up mode (point-like singularity)
- blow-up mode fixed by non-perturbative effects
  volume by α'-corrections $\rightarrow$ exponentially large

Experimental predictions

- particle accelerators
  - Large TeV dimensions   seen by SM gauge interactions
    - $\Rightarrow$ KK resonances of SM gauge bosons   I.A. '90
      - $\longrightarrow$ see Freitas' talk next
  - Extra large submm dimensions   transverse
    - $\Rightarrow$ missing energy from gravity radiation in the bulk [10]
  - string physics and possible strong gravity effects [12]
- microgravity experiments [18]
  - gravity modifications at short distances
  - new submillimeter forces

Giudice-Rattazzi-Wells '98





Angular distribution ⇒ spin of the graviton

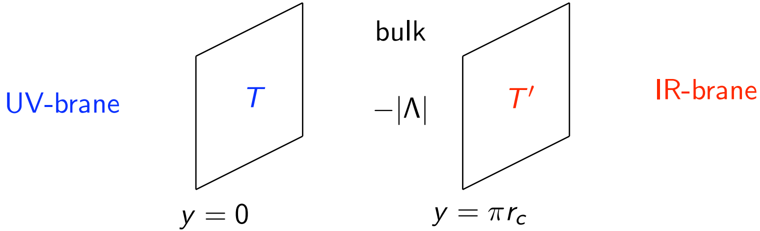
Limits on $R_\perp$ in mm

Experiment	$R_\perp(n=2)$	$R_\perp(n=4)$	$R_\perp(n=6)$
Collider bounds			
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}
Astrophysics/cosmology bounds			
SN1987A	3×10^{-4}	1×10^{-8}	6×10^{-10}
COMPTEL	5×10^{-5}	-	-

Randal Sundrum models

spacetime = slice of AdS_5 our universe = 4d flat boundary

$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$



- fine-tuned tensions: $T = -T' = 24M^3k^2$ $\Lambda = -24M^3k^2$
- exponential hierarchy: $M_W = M_P e^{-2\pi k r_c}$ $M_P^2 \sim M^3/k$
- 4d gravity localized on the UV-brane, but KK gravitons on the IR

- main prediction: spin-2 resonances at the TeV scale

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

  weakly coupled for $m_n < M\, e^{-2\pi k r_c}$ $\quad \Rightarrow k < M$

- viable models: Standard Model gauge bosons in the bulk,

  fermions near the UV-brane, Higgs on the IR-brane

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

  composite Higgs models, technicolor-type $\quad g_{YM} = M/k > 1$ [7]

Massive string vibrations

indirect effects: virtual exchanges $\Rightarrow$ effective interactions

e.g. four-fermion operators

Actual limits: Matter fermions on

- same set of branes $\Rightarrow M_s \gtrsim 500$ GeV   dim-8: $\frac{g^2}{M_s^4}(\bar{\psi}\partial\psi)^2$

- brane intersections $\Rightarrow M_s \gtrsim 2-3$ TeV   dim-6: $\frac{g^2}{M_s^2}(\bar{\psi}\psi)^2$

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

High energies $\Rightarrow$

- direct production: string physics

- strong gravity: production of micro-black holes? [17]

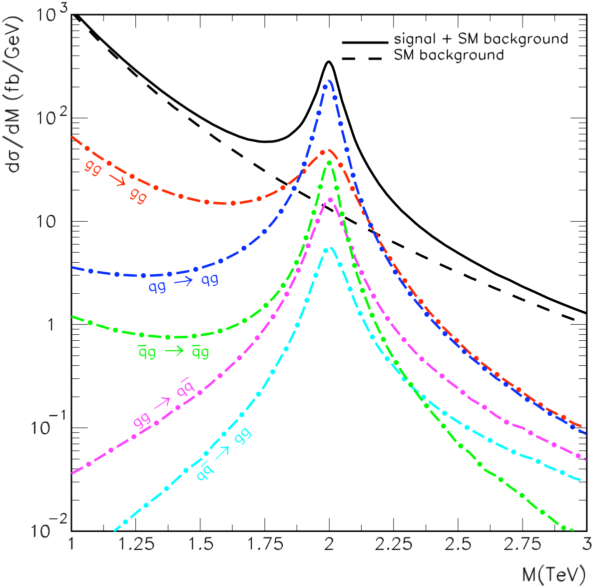
Giddings-Thomas, Dimopoulos-Landsberg '01

Universal deviation from Standard Model in jet distribution

$M_s = 2$ TeV

Width = 15-150 GeV

Anchordoqui-Goldberg-Lüst-Nawata-Taylor-Stieberger '08 [12]



Tree N-point superstring amplitudes in 4 dims

involving at most 2 fermions and gluons:

completely model independent for any string compactification

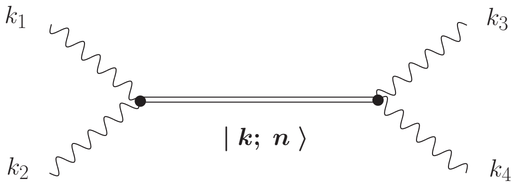
any number of supersymmetries, even none

No intermediate exchange of KK, windings or graviton emmission

Universal sum over infinite exchange of string Regge (SR) excitations:

masses: $M_n^2 = M_s^2\, n$

maximal spin: $n+1$



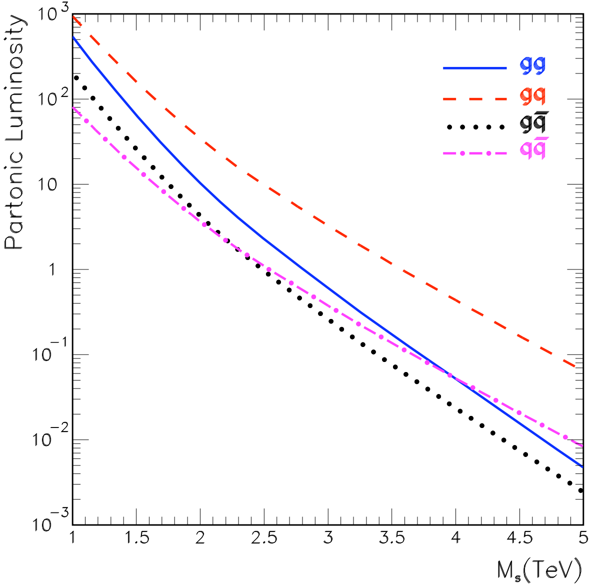
Parton luminosities in pp above TeV

are dominated by gq, gg

$\Rightarrow$ model independent [13]

$gq \rightarrow gq$

$gg \rightarrow gg$, $gg \rightarrow q\bar{q}$



Cross sections

$$\boxed{\begin{array}{ccc} |\mathcal{M}(gg \to gg)|^2 & , & |\mathcal{M}(gg \to q\bar{q})|^2 \\ |\mathcal{M}(q\bar{q} \to gg)|^2 & , & |\mathcal{M}(qg \to qg)|^2 \end{array}} \Bigg\}$$

model independent
for any compactification

Lüst-Stieberger-Taylor '08

$$|\mathcal{M}(gg \to gg)|^2 = g_{YM}^4 \left(\tfrac{1}{s^2} + \tfrac{1}{t^2} + \tfrac{1}{u^2}\right) \times \left[\tfrac{9}{4}\left(s^2 V_s^2 + t^2 V_t^2 + u^2 V_u^2\right) - \tfrac{1}{3}\left(sV_s + tV_t + uV_u\right)^2\right]$$

$$|\mathcal{M}(gg \to q\bar{q})|^2 = g_{YM}^4 \frac{t^2+u^2}{s^2} \left[\frac{1}{6}\,\frac{1}{tu}\,(tV_t + uV_u)^2 - \frac{3}{8}\,V_t\,V_u\right]$$

$M_s = 1$

$V_s = -\frac{tu}{s}\ B(t,u) = 1 - \frac{2}{3}\pi^2\, tu + \ldots \qquad V_t : s \leftrightarrow t \qquad V_u : s \leftrightarrow u$

YM limits agree with e.g. book "*Collider Physics*" by Barger, Phillips

Energy threshold for black hole production :

$$E_{\rm BH} \simeq M_s/g_s^2 \quad \leftarrow \text{ string coupling}$$

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_*

$g_s \simeq \alpha_{\rm YM} \sim 0.1$; Regge excitations : $M_n^2 = M_s^2 n \Rightarrow$

gauge coupling

Energy threshold of n-th string excitation: $E_n \simeq M_s \sqrt{n} \Rightarrow$

production of $n \sim 1/g_s^4 \sim 10^4$ string states before reach $E_{\rm BH}$ [7]

SUSY in the bulk?

- global SUSY: no need to be there   at least for hierarchy

- SUGRA: probably unbroken in the bulk $\Rightarrow$

very weakly broken (volume suppressed)

New forces at submm scales   e.g. radion, gauge fields

- Radion $\equiv \ln V_\perp$

- mass: $(\mathrm{TeV})^2/M_P \sim 10^{-4}$ eV $\rightarrow$ mm range
- coupling: $\frac{1}{m}\frac{\partial m}{\partial \ln V_\perp} = \sqrt{\frac{n}{n+2}} \times$ gravity   I.A.-Benakli-Maillard-Laugier '02

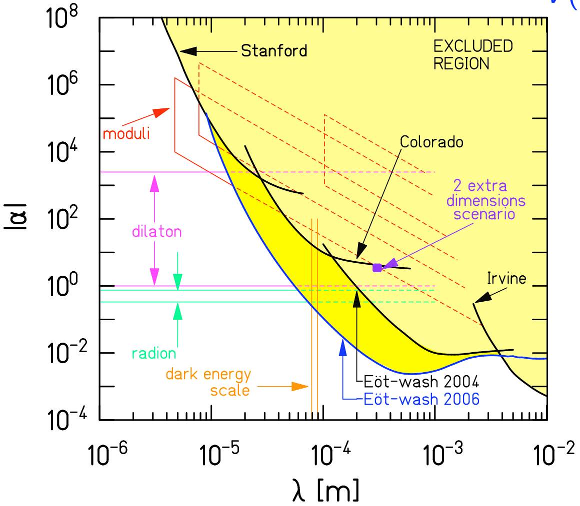
$\Rightarrow$ can be experimentally tested for all $n \geq 2$ [5]

- Light $U(1)$ gauge bosons: no derivative couplings

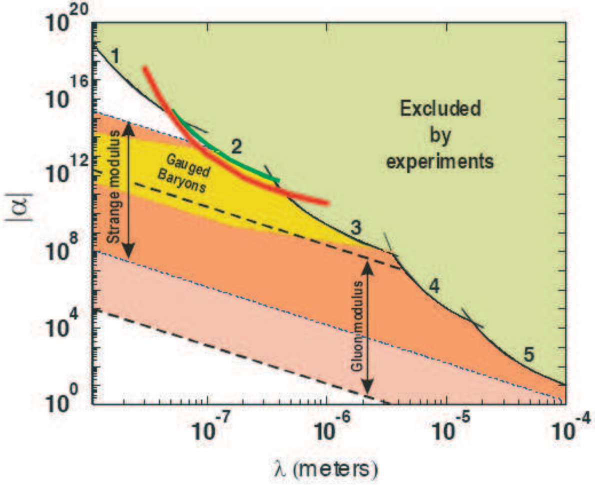
$\Rightarrow$ for the same mass much stronger than gravity: $\gtrsim\ 10^6$

Experimental limits on short distance forces

$$V(r) = -G\frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$



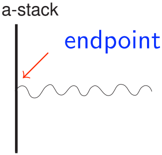
Radion $\Rightarrow M_* \gtrsim 6$ TeV 95% CL Adelberger et al. '06 an order of magnitude improvement in the range 10-200 nm Decca et al '07



5: Colorado 4: Stanford 3: Lamoureaux 1: Mohideen et al.

A D-brane embedding of the Standard Model

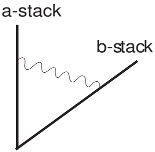
Generic spectrum: N coincident branes $\Rightarrow$ $U(N)$



endpoint transformation: $\mathbf{N}_a$ or $\bar{\mathbf{N}}_a$ $U(1)_a$ charge: $+1$ or -1

$\Rightarrow$ "baryon" number

- open strings from the same stack $\Rightarrow$ adjoint gauge multiplets of $U(N_a)$
- stretched between two stacks $\Rightarrow$ bifundamentals of $U(N_a) \times U(N_b)$



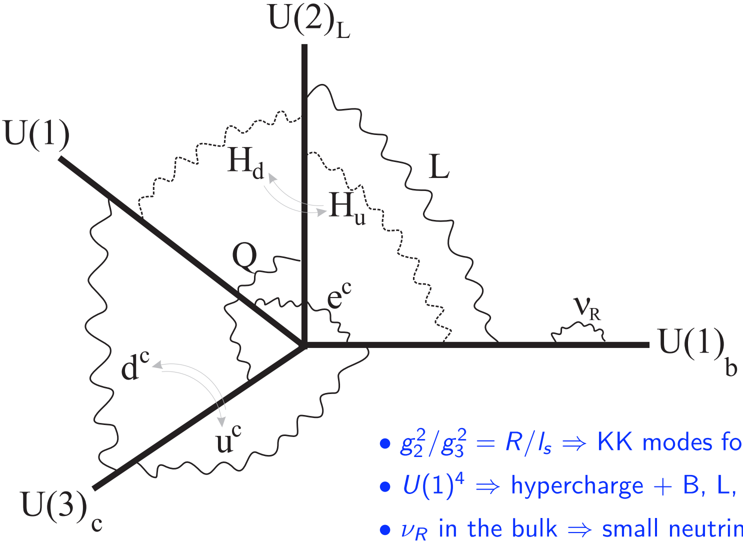
- oriented strings $\Rightarrow$ need at least 4 brane-stacks

- existence of bulk with large dimensions $\Rightarrow$

minimal choice: $U(3) \times U(2) \times U(1) \times U(1)_{\rm bulk}$

color branes (g_3) weak branes (g_2)

Standard Model on D-branes I.A.-Kiritsis-Rizos-Tomaras '02



- $g_2^2/g_3^2 = R/l_s \Rightarrow$ KK modes for $SU(2)_L$ [4] [26]
- $U(1)^4 \Rightarrow$ hypercharge + B, L, PQ global
- ν_R in the bulk $\Rightarrow$ small neutrino masses [24]
- $U(1)$ on top of $U(2)$ or $U(3)$ $\Rightarrow$ prediction for $\sin^2\theta_W$ [25]

The remaining three $U(1)$'s : anomalous

Green-Schwarz anomaly cancellation $\Rightarrow$

• they become massive (absorb three axions)

gauge field: $\delta A = d\Lambda \quad \Rightarrow \quad$ axion: $\delta a = -M\Lambda$

$$-\frac{1}{4g_A^2}\, F_A^2 - \frac{1}{2}\,(da + MA)^2 + \frac{a}{M}\, k_I^A\, \mathrm{Tr} F_I \wedge F_I$$

cancel the anomaly

$\Rightarrow \;\; U(1)_A$ mass: $\;\; m_A = g_A\, M$

• 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

R-neutrinos: open strings in the bulk

R-neutrino: $\nu_R(x, y)$ y: bulk coordinates

Arkani Hamed-Dimopoulos-Dvali-March Russell '98

Dienes-Dudas-Gherghetta '98

$$S_{int} = g_s \int d^4x\, H(x)\, L(x)\, \nu_R(x, y = 0)$$

$\langle H \rangle = v \;\Rightarrow\;$ mass-term: $\dfrac{g_s v}{R_\perp^{n/2}} \nu_L \nu_R^0 \;\leftarrow$ 4d zero-mode

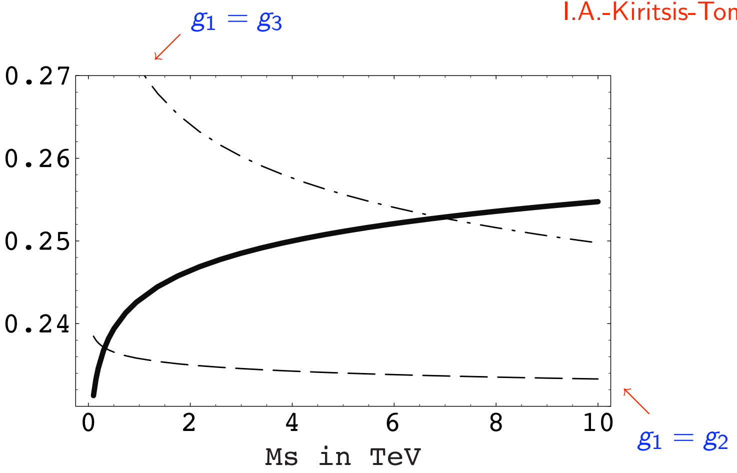
Dirac neutrino masses: $m_\nu \simeq \dfrac{g_s v}{R_\perp^{n/2}} \simeq v \dfrac{M_s}{M_p}$

$\simeq 10^{-3} - 10^{-2}$ eV for $M_s \simeq 1 - 10$ TeV

$m_\nu << 1/R_\perp \Rightarrow$ KK modes unaffected [22]

$\sin^2\theta_W(M_s)$

I.A.-Kiritsis-Tomaras '00



$\Rightarrow$ correct prediction for $\sin^2\theta_W$ for $M_s \sim$ a few TeV

Conclusions

TeV strings and large extra dimensions: Physical reality or imagination?

- Well motivated theoretical framework

  with many testable experimental predictions

  new resonances, missing energy

- Stimulus for micro-gravity experiments

  look for new forces at short distances

  higher dim graviton, scalars, gauge fields

But: - unification has to be dropped

- physics is radically changed above string scale

LHC: will explore the physics beyond the Standard Model