An introduction to extra dimensions and string phenomenology

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Outline

1. Physical context and motivations
2. High string scale - heterotic string
3. High string scale - type II and D-branes
4. Low string scale and large extra dimensions
5. Experimental predictions

Bibliography

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Fundamental interactions

force	range	intensity of 2 protons	intensity at 10^{-16} cm
Gravitation	∞	10^{-38}	10^{-30}
Electromagnetic	∞	10^{-2}	10^{-2}
Weak (radioactivity β)	10^{-15} cm	10^{-5}	10^{-2}
Strong (nuclear forces)	10^{-12} cm	1	10^{-1}

At what distance, gravitation becomes comparable to the other interactions?

Planck length: 10^{-33} cm $\rightarrow M_{\rm Planck} \simeq 10^{15} \times$ the LHC energy!

Newton's law

$m \bullet \longleftarrow r \longrightarrow \bullet m \qquad F_{\rm grav} = G_N \frac{m^2}{r^2} \qquad G_N^{-1/2} = M_{\rm Planck} = 10^{19}$ GeV

Compare with electric force: $F_{\rm el} = \frac{e^2}{r^2} \Rightarrow$

effective dimensionless coupling $G_N m^2$ or in general $G_N E^2$ at energies E

$E = m_{\rm proton} \Rightarrow \frac{F_{\rm grav}}{F_{\rm el}} = \frac{G_N m_{\rm proton}^2}{e^2} \simeq 10^{-40}$ [17]

$\Rightarrow$ Gravity is very weak !

Standard Model of electroweak + strong forces

- Quantum Field Theory   Quantum Mechanics + Special Relativity
- Principle: gauge invariance $U(1) \times SU(2) \times SU(3)$

Very accurate description of physics at present energies   17 parameters

1. mediators of gauge interactions (vectors): photon, $W^{\pm}$, Z + **8 gluons**
2. matter (fermions): (leptons + quarks) $\times$ 3

   electron, positron, neutrino   (up, down)$_{\textbf{3 colors}}$
3. Higgs sector: new scalar(s) particle(s)

Electroweak symmetry : spontaneously broken

$SU(2) \times U(1) \to U(1)_{\rm photon} \Rightarrow W^{\pm}, Z^0$ massive, photon massless

$\nwarrow$ observed at LEP

a new particle is needed : Higgs boson (scalar)

- break the EW symmetry at ~ 100 GeV
- generate mass for all elementary particles

through their interaction with the Higgs field

Englert-Brout-Higgs mechanism

Englert-Brout; Higgs; Guralnik-Hagen-Kibble '64

Its discovery was one of the main goals of LHC

Beyond the Standard Model : Why?

- to include gravity in a consistent quantum theory

  longstanding dream of unification of all fundamental forces of Nature

- origin of electroweak (EW) symmetry breaking

  what is behind the Brout-Englert-Higgs mechanism?

- hierarchy of masses and force intensities EW/gravity $\sim 10^{32}$

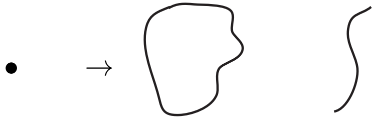
  stability at the quantum level $\Rightarrow$

  fine-tuning of parameters in 32 decimal places!

- neutrino masses and oscillations
- origin of Dark Matter in the Universe

String theory: Quantum Mechanics + General Relativity

point particle $\rightarrow$ extended objects



particles $\equiv$ string vibrations

- quantum gravity
- framework of unification of all interactions
- "ultimate" theory: · ultraviolet finite

  · no free parameters

mass scale (tension): $M_{\rm string} \leftrightarrow$ size: $l_{\rm string}$

rigid string : known particles (massless)

vibrations : infinity of massive particles

Strings and extra dimensions

Consistent theory $\Rightarrow$ 9 spatial dimensions !

six new dimensions of space

matter and gauge interactions may be localized

in less than 9 dimensions $\Rrightarrow$

our universe on a membrane ? [14]

p-plane: extended in p spatial dimensions

$p = 0$: particle, $p = 1$: string,...

Extra Dimensions

how they escape observation?

finite size R Kaluza and Klein 1920

energy cost to send a signal:

$E > R^{-1} \leftarrow$ compactification scale

experimental limits on their size

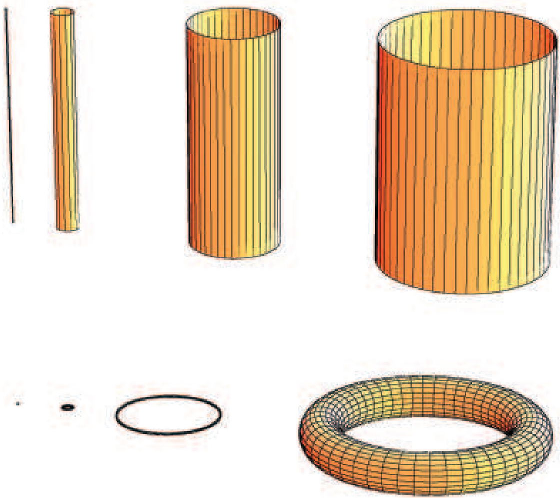
light signal $\Rightarrow$ $E \gtrsim 1$ TeV

$R \lesssim 10^{-16}$ cm

how to detect their existence?

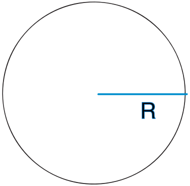
motion in the internal space $\Rightarrow$ mass spectrum in 3d

Dimensions D=??



example: - one internal circular dimension

- light signal



plane waves e^{ipy} periodic under $y \to y + 2\pi R$

$\Rightarrow$ quantization of internal momenta: $p = \frac{n}{R}$; $n = 0, 1, 2, \ldots$

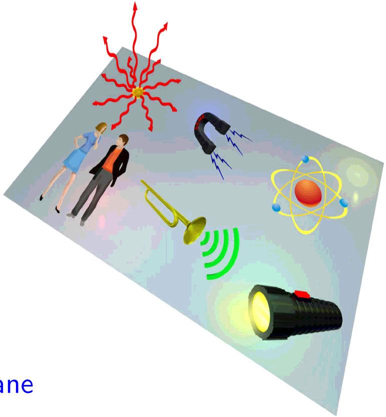
$\Rightarrow$ 3d: tower of Kaluza Klein particles with masses $M_n = n/R$

$$p_0^2 - \vec{p}^2 - p_5^2 = 0 \;\Rightarrow\; p^2 = p_5^2 = \frac{n^2}{R^2}$$

$E >> R^{-1}$: emission of many massive photons

$\Leftrightarrow$ propagation in the internal space [10]

Our universe on a membrane

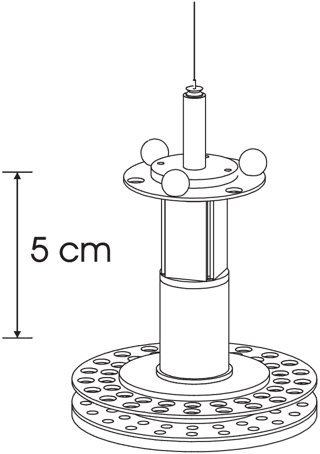


Two types of new dimensions:

- longitudinal: along the membrane
- transverse: “hidden” dimensions

  only gravitational signal $\Rightarrow R_\perp \lesssim 1$ mm !

Adelberger et al. '06



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

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

Low scale gravity

Extra large $\perp$ dimensions can explain the apparent weakness of gravity

total force = observed force $\times$ volume $\perp$

total force $\simeq \mathcal{O}(1)$ at 1 TeV

n dimensions of size $R_\perp$

$n = 1: \ R_\perp \simeq 10^8$ km — excluded

$n = 2: \ R_\perp \simeq 0.1$ mm $\quad (10^{-12}$ GeV$)$

possible

$n = 6: \ R_\perp \simeq 10^{-13}$ mm $\quad (10^{-2}$ GeV$)$

- distances $> R_\perp$: gravity 3d

  however for $< R_\perp$: gravity (3+n)d

- strong gravity at 10^{-16} cm $\leftrightarrow 10^3$ GeV

10^{30} times stronger than thought previously! [19]

Low scale gravity

Extra large $\perp$ dimensions can explain the apparent weakness of gravity

total force = observed force $\times$ volume $\perp$ [5]

$$\begin{array}{ccccc} \uparrow & & \uparrow & & \uparrow \\ G_N^* E^{2+n} & = & G_N E^2 & \times & V_\perp E^n \end{array}$$

$G_N^* = M_*^{-(2+n)}$: $(4+n)$-dim gravitational constant

total force $\simeq \mathcal{O}(1)$ at 1 TeV

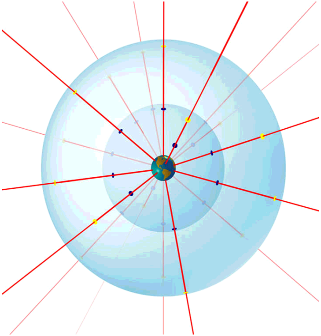
n dimensions of size $R_\perp$

$\Rightarrow \; V_\perp = R_\perp^n$

$\Rightarrow M_P^2 = M_*^{2+n} R_\perp^n$ for $M_* \simeq 1$ TeV $\Rightarrow (R_\perp M_*)^n \sim 10^{32}$

Gravity modification at submillimeter distances

Newton's law: force decreases with area



3d: force $\sim 1/r^2$

$(3+n)$d: force $\sim 1/r^{2+n}$

observable for $n = 2$: $1/r^4$ with $r << .1$ mm [16]

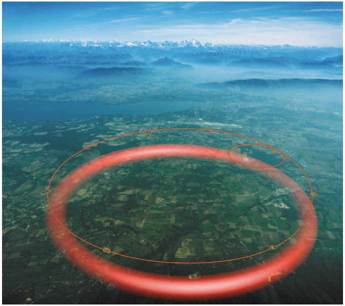
Connect string theory to the real world

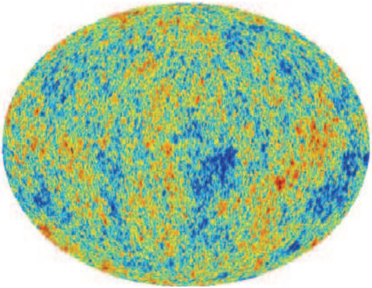
- Is string theory a tool for strong coupling dynamics

  or a theory of fundamental forces?

- If theory of Nature can string theory describe

  both particle physics and cosmology?





Problem of scales

- describe high energy (SUSY?) extension of the Standard Model

  unification of all fundamental interactions

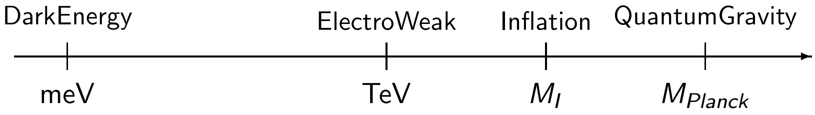
- incorporate Dark Energy

  simplest case: infinitesimal (tuneable) +ve cosmological constant

- describe possible accelerated expanding phase of our universe

  models of inflation (approximate de Sitter)

$\Rightarrow$ 3 very different scales besides M_{Planck} :



At what energies strings may be observed?

Very different answers depending mainly on the value of the string scale M_s

Before 1994: $M_s \simeq M_{\rm Planck} \sim 10^{18}$ GeV $\quad l_s \simeq 10^{-32}$ cm $\quad$ After 1994:

- arbitrary parameter : Planck mass $M_P \longrightarrow$ TeV

- physical motivations $\Rrightarrow$ favored energy regions:

- High : $\begin{cases} M_P^* \simeq 10^{18} \text{ GeV} & \text{Heterotic scale} \\ M_{\rm GUT} \simeq 10^{16} \text{ GeV} & \text{Unification scale} \end{cases}$

- Intermediate : around 10^{11} GeV ($M_s^2/M_P \sim$ TeV)

  SUSY breaking, strong CP axion, see-saw scale

- Low : TeV (hierarchy problem)

High string scale

perturbative heterotic string : the most natural for SUSY and unification

gravity and gauge interactions have same origin

massless excitations of the closed string

But mismatch between string and GUT scales:

$M_s = g_H M_P \simeq 50 M_{\rm GUT}$ $\quad g_H^2 \simeq \alpha_{\rm GUT} \simeq 1/25$ [34]

in GUTs only one prediction from 3 gauge couplings unification: $\sin^2\theta_W$

introduce large threshold corrections or strong coupling $\rightarrow M_s \simeq M_{\rm GUT}$

but loose predictivity [25]

Heterotic string

gravity + gauge kinetic terms [35]

$$\int [d^{10}x] \, \frac{1}{g_H^2} M_H^8 \, \mathcal{R}^{(10)} + \int [d^{10}x] \, \frac{1}{g_H^2} M_H^6 \, \mathcal{F}_{MN}^2$$

simplified units: $2 = \pi = 1$

Compactification in 4 dims on a 6-dim manifold of volume $V_6 \Rightarrow$

$$\int [d^4x] \, \underbrace{\frac{V_6}{g_H^2}}_{M_P^2} M_H^8 \, \mathcal{R}^{(4)} + \int [d^4x] \, \underbrace{\frac{V_6}{g_H^2}}_{1/g^2} M_H^6 \, \mathcal{F}_{\mu\nu}^2 \quad \Rightarrow$$

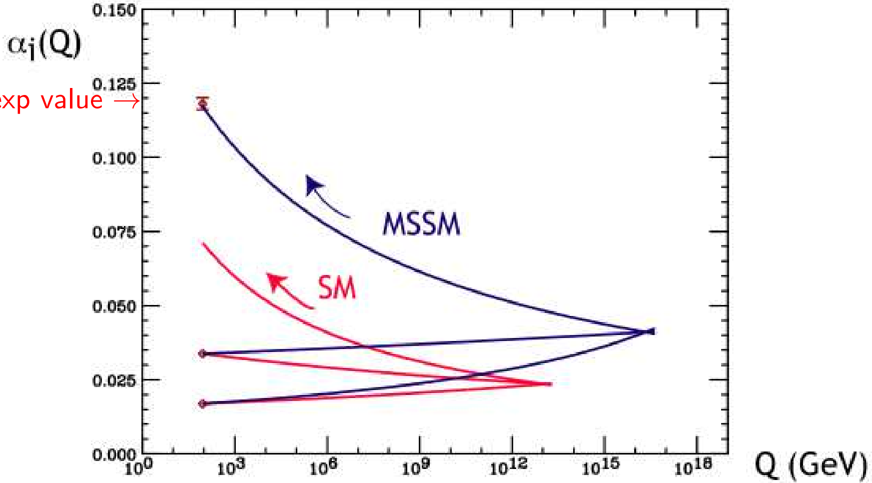
$$M_P^2 = \frac{1}{g^2} M_H^2 \quad \frac{1}{g^2} = \frac{1}{g_H^2} V_6 M_H^6 \quad \Rightarrow \quad M_H = g M_P \quad g_H = g\sqrt{V_6} M_H^3$$

$g_H \lesssim 1 \Rightarrow V_6 \sim$ string size

GUT prediction of QCD coupling

input $\alpha_{\rm em}, \sin^2\theta_W \quad \Rightarrow \quad$ output α_3 [35]

exp value →



Open strings and D-branes

string propagation in space-time $\Rightarrow$ 2-dim world-sheet (τ,σ) $X^\mu(\tau,\sigma)$

τ: time, $\sigma\in[0,\pi]$: spatial extension of the string

closed strings $\Rightarrow$ σ: periodic $X^\mu(\tau,0)=X^\mu(\tau,\pi)$

open string $\Rightarrow$ endpoints: $\sigma=0,\pi$ world-sheet boundaries

they also carry gauge charges

D-branes = hypersurfaces where open strings can end

Dp-brane: parallel dimensions: $X^1,\dots,X^p$ (also time X^0)

$\partial_\sigma X^\mu=0$ at $\sigma=0$ normal derivative vanishes

Newmann boundary conditions $\Rightarrow$ free propagation along the boundary

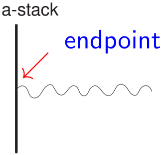
transverse dimensions: $X^{p+1},\dots,X^9$

$X^\mu=X_0^\mu$ at $\sigma=0$ $(\partial_\tau X^\mu=0$ at $\sigma=0)$

Dirichlet conditions: endpoint fixed at the boundary

D-brane spectrum

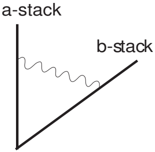
Generic spectrum: N coincident branes $\Rightarrow$ $U(N)$



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 $U(N_a) \times U(N_b)$



non-oriented strings $\Rightarrow$ also:

- orthogonal and symplectic groups $SO(N), Sp(N)$

- matter in antisymmetric + symmetric reps

Non oriented strings ⇒ orientifold planes

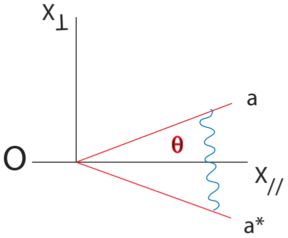
where closed strings change orientation

⇒ mirror branes   identified with branes under orientifold action

• strings stretched between two mirror stacks

Orientifold →

$X_\perp \to -X_\perp$



⇒ antisymmetric or symmetric of $U(N_a)$

Minimal Standard Model embedding

General analysis using 3 brane stacks [52]

$$\Rightarrow \; U(3) \times U(2) \times U(1)$$

antiquarks u^c, d^c $(\bar{3}, 1)$:

antisymmetric of $U(3)$ or bifundamental $U(3) \leftrightarrow U(1)$

$\Rightarrow$ 3 models: antisymmetric is u^c, d^c or none

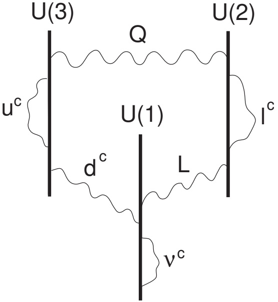
N_i stack of D-branes: $U(N_i) = SU(N_i) \times U(1)_i$

gauge couplings: $\alpha_{N_i} = \dfrac{g_{N_i}^2}{4\pi}$ and α_i

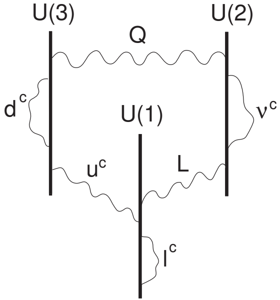
normalization: $\mathrm{Tr}\, T^a T^b = \dfrac{1}{2}\delta^{ab} \Rightarrow \alpha_i = \dfrac{\alpha_{N_i}}{2N_i}$

$$Y = c_1 Q_1 + c_2 Q_2 + c_3 Q_3 \Rightarrow \frac{1}{g_Y^2} = \frac{2c_1^2}{g_1^2} + \frac{4c_2^2}{g_2^2} + \frac{6c_3^2}{g_3^2}$$

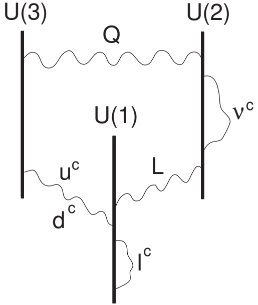
$$\sin^2\theta_W = \frac{g_Y^2}{g_2^2 + g_Y^2} = \frac{1}{g_2^2/g_Y^2 + 1} = \frac{1}{1 + 4c_2^2 + 2c_1^2 g_2^2/g_1^2 + 6c_3^2 g_2^2/g_3^2}$$



Model A

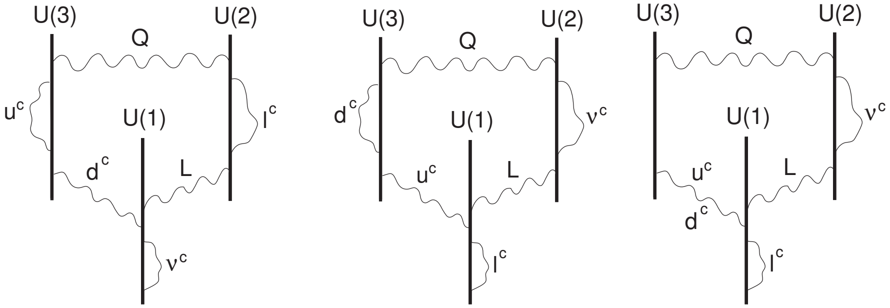


Model B



Model C

Q	$(\mathbf{3},\mathbf{2};1,1,0)_{1/6}$	$(\mathbf{3},\mathbf{2};1,\varepsilon_Q,0)_{1/6}$	$(\mathbf{3},\mathbf{2};1,\varepsilon_Q,0)_{1/6}$
u^c	$(\bar{\mathbf{3}},\mathbf{1};2,0,0)_{-2/3}$	$(\bar{\mathbf{3}},\mathbf{1};-1,0,1)_{-2/3}$	$(\bar{\mathbf{3}},\mathbf{1};-1,0,1)_{-2/3}$
d^c	$(\bar{\mathbf{3}},\mathbf{1};-1,0,\varepsilon_d)_{1/3}$	$(\bar{\mathbf{3}},\mathbf{1};2,0,0)_{1/3}$	$(\bar{\mathbf{3}},\mathbf{1};-1,0,-1)_{1/3}$
L	$(\mathbf{1},\mathbf{2};0,-1,\varepsilon_L)_{-1/2}$	$(\mathbf{1},\mathbf{2};0,\varepsilon_L,1)_{-1/2}$	$(\mathbf{1},\mathbf{2};0,\varepsilon_L,1)_{-1/2}$
l^c	$(\mathbf{1},\mathbf{1};0,2,0)_{1}$	$(\mathbf{1},\mathbf{1};0,0,-2)_{1}$	$(\mathbf{1},\mathbf{1};0,0,-2)_{1}$
ν^c	$(\mathbf{1},\mathbf{1};0,0,2\varepsilon_\nu)_{0}$	$(\mathbf{1},\mathbf{1};0,2\varepsilon_\nu,0)_{0}$	$(\mathbf{1},\mathbf{1};0,2\varepsilon_\nu,0)_{0}$

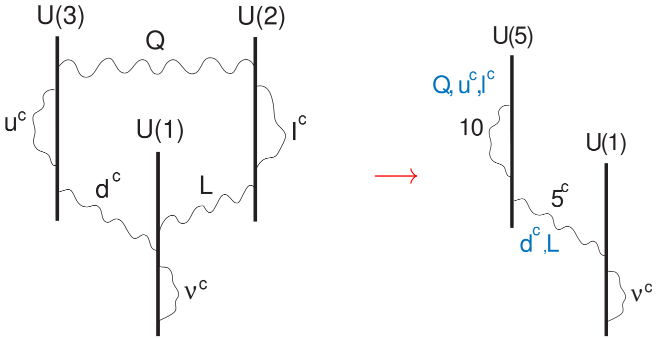


Model A **Model B** **Model C**

$$Y_A = -\frac{1}{3}Q_3 + \frac{1}{2}Q_2 \qquad Y_{B,C} = \frac{1}{6}Q_3 - \frac{1}{2}Q_1$$

$$\sin^2\theta_W = \left.\frac{1}{2+2\alpha_2/3\alpha_3}\right|_{\alpha_2=\alpha_3} = \frac{3}{8} \qquad \left.\frac{1}{1+\alpha_2/2\alpha_1+\alpha_2/6\alpha_3}\right|_{\alpha_2=\alpha_3} = \frac{6}{7+3\alpha_2/\alpha_1}$$

$SU(5)$ GUT



Intersecting branes: ‘perfect’ for SM embedding

product of unitary gauge groups (brane stacks) and bi-fundamental reps

but no unification: no prediction for M_s, independent gauge couplings

however GUTs: problematic:

- no perturbative $SO(10)$ spinors
- no top-quark Yukawa coupling in $SU(5)$: $10\,10\,5_H$

  $SU(5)$ is part of $U(5) \Rightarrow U(1)$ charges : 10 charge 2 ; 5_H charge ± 1

  $\Rightarrow$ cannot balance charges with $SU(5)$ singlets

  can be generated by D-brane instantons but . . .

$\rightarrow$ Non-perturbative M/F-theory models:

combine good properties of heterotic and intersecting branes

but lack exact description for systematic studies

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 [36]

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 [22]

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

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

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

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

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

Type I/II strings: gravity and gauge interactions have different origin

gravity + gauge kinetic terms

$$\int [d^{10}x] \, \frac{1}{g_s^2} M_s^8 \, \mathcal{R}^{(10)} + \int [d^{p+1}x] \, \frac{1}{g_s} M_s^{p-3} \, \mathcal{F}_{MN}^2$$ [23]

Compactification in 4 dims $\Rightarrow$

$$\int [d^4x] \, \underbrace{\frac{V_6}{g_s^2} M_s^8}_{M_P^2} \, \mathcal{R}^{(4)} + \int [d^4x] \, \underbrace{\frac{V_\parallel}{g_s} M_s^{p-3}}_{1/g^2} \, \mathcal{F}_{\mu\nu}^2 \qquad V_6 = V_\parallel V_\perp$$

$\Rightarrow$

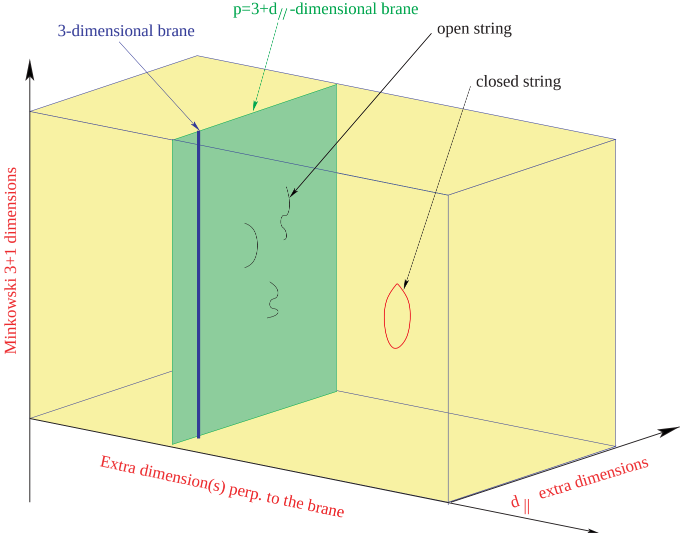
$$g_s = g^2 V_\parallel M_s^{p-3} \lesssim 1 \Rightarrow V_\parallel \sim \text{string size}$$

$$\Rightarrow \quad M_P^2 = \frac{V_\perp}{g_s^2} M_s^{2+n} \qquad g_s \simeq g^2$$

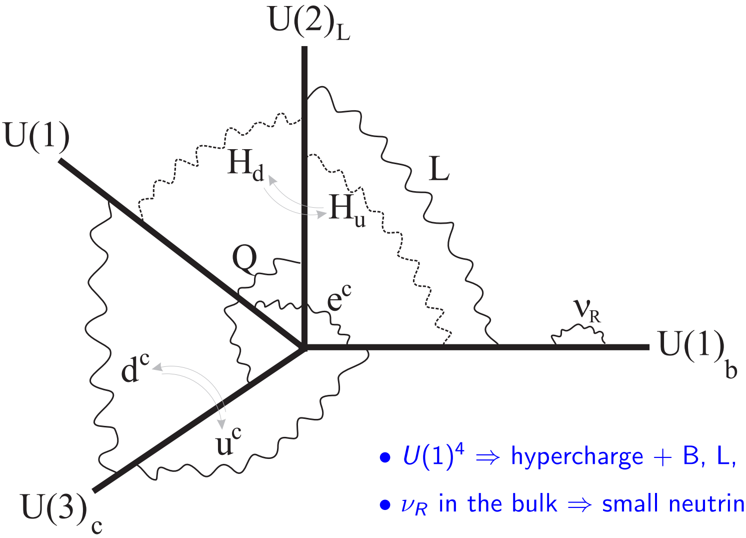
Braneworld

2 types of compact extra dimensions:

- parallel ($d_{\|}$): $\lesssim 10^{-16}$ cm (TeV) [34]
- transverse ($\perp$): $\lesssim 0.1$ mm (meV)



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



- $U(1)^4 \Rightarrow$ hypercharge + B, L, PQ global
- ν_R in the bulk $\Rightarrow$ small neutrino masses

R-neutrinos: in the bulk

Arkani Hamed-Dimopoulos-Dvali-March Russell '98
Dienes-Dudas-Gherghetta '98 Dvali-Smirnov '98

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

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

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

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

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

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

Experimental predictions

- No little hierarchy problem:

  radiative electroweak symmetry breaking with no logs

  $\Lambda \sim$ a few TeV and $m_H^2 =$ a loop factor $\times \Lambda^2$

- particle accelerators

  - Large TeV dimensions seen by gauge interactions

  - Extra large hidden dimensions transverse $\Rightarrow$ strong gravity

  - other accelerator signatures

- microgravity experiments

  - gravity modifications at short distances

  - new submillimeter forces

Accelerator signatures: 4 different scales

- Gravitational radiation in the bulk ⇛ missing energy

  present LHC bounds: $M_* \gtrsim 4 - 9$ TeV

- Massive string vibrations ⇛ e.g. resonances in dijet distribution [42]

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

  higher spin excitations of quarks and gluons with strong interactions

  present LHC limits: $M_s \gtrsim 7$ TeV

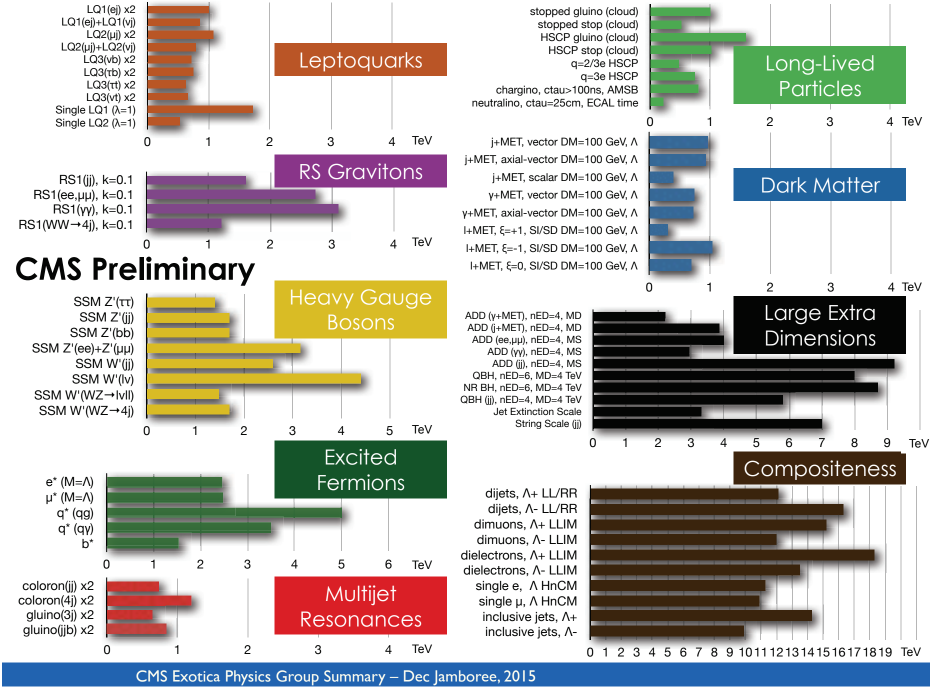
- Large TeV dimensions ⇛ KK resonances of SM gauge bosons I.A. '90

  $$M_k^2 = M_0^2 + k^2/R^2 \;\; ; \;\; k = \pm 1, \pm 2, \ldots$$

  experimental limits: $R^{-1} \gtrsim 0.5 - 4$ TeV (UED - localized fermions) [45]

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

  masses suppressed by a loop factor from M_s [50]


CMS Preliminary
Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(ττ) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
RS Gravitons
RS1(jj), k=0.1
RS1(ee,μμ), k=0.1
RS1(γγ), k=0.1
RS1(WW→4j), k=0.1
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
SSM W'(WZ→4j)
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
chargino, ctau>100ns, AMSB
neutralino, ctau=25cm, ECAL time
Dark Matter
j+MET, vector DM=100 GeV, Λ
j+MET, axial-vector DM=100 GeV, Λ
j+MET, scalar DM=100 GeV, Λ
γ+MET, vector DM=100 GeV, Λ
γ+MET, axial-vector DM=100 GeV, Λ
l+MET, ξ=+1, SI/SD DM=100 GeV, Λ
l+MET, ξ=-1, SI/SD DM=100 GeV, Λ
l+MET, ξ=0, SI/SD DM=100 GeV, Λ
Large Extra Dimensions
ADD (γ+MET), nED=4, MD
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
ADD (jj), nED=4, MS
QBH, nED=6, MD=4 TeV
NR BH, nED=6, MD=4 TeV
QBH (jj), nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
TeV
CMS Exotica Physics Group Summary – Dec Jamboree, 2015

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

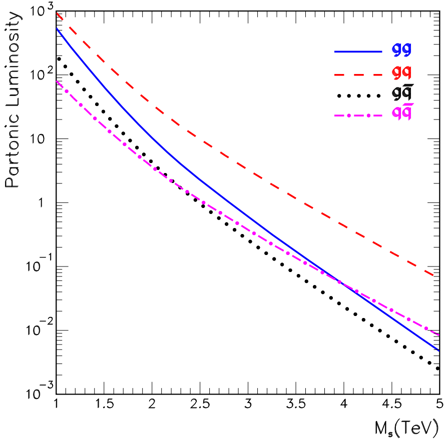
Universal sum over infinite exchange of string (Regge) excitations

Parton luminosities in pp above TeV

are dominated by gq, gg

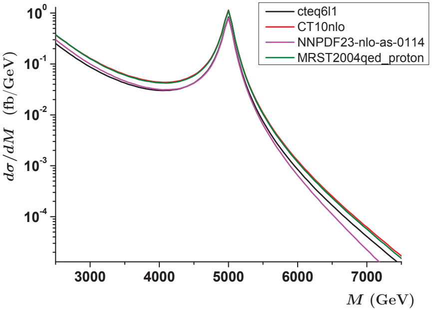
$\Rightarrow$ model independent

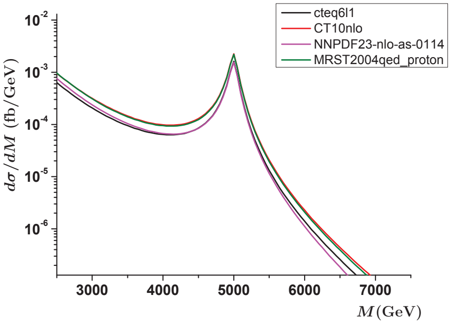
$gq \to gq$, $gg \to gg$, $gg \to q\bar{q}$



String Resonances production at Hadron Colliders

I.A.-Anchordoqui-Dai-Feng-Goldberg-Huang-Lüst-Stojkovic-Taylor '14

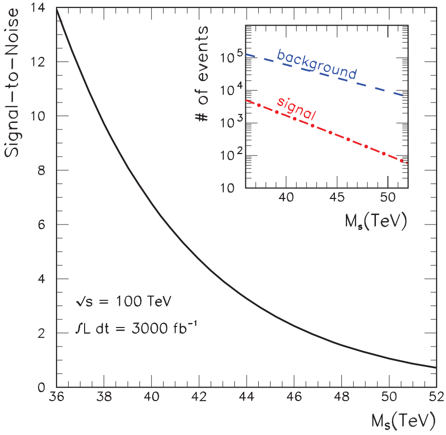


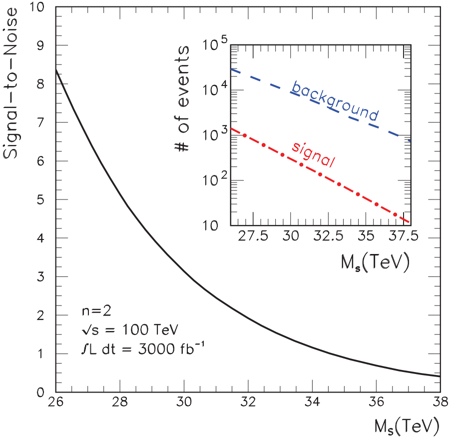


$M_s = 5$ TeV: dijet at LHC14 $\gamma +$ jet

String Resonances production at Hadron Colliders

I.A.-Anchordoqui-Dai-Feng-Goldberg-Huang-Lüst-Stojkovic-Taylor ’14

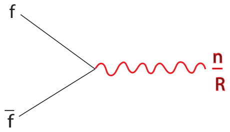




[40]

Localized fermions (on 3-brane intersections)

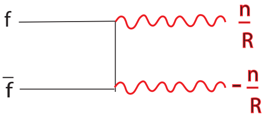
⇒ single production of KK modes I.A.-Benakli '94



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

Otherwise KK momentum conservation [47]

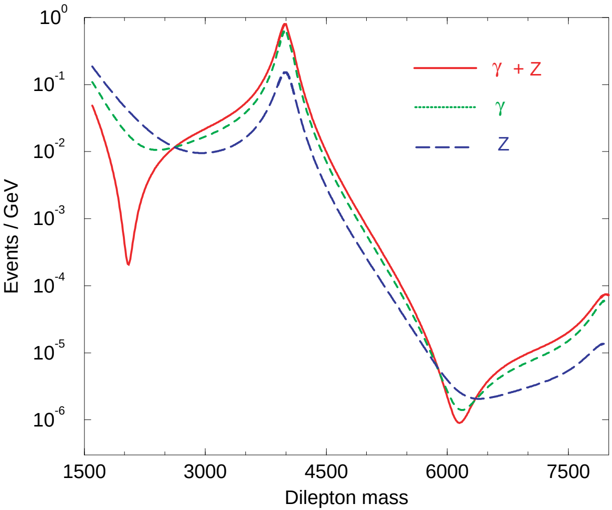
⇒ pair production of KK modes (universal dims)



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

Servant-Tait '02

$R^{-1} = 4$ TeV

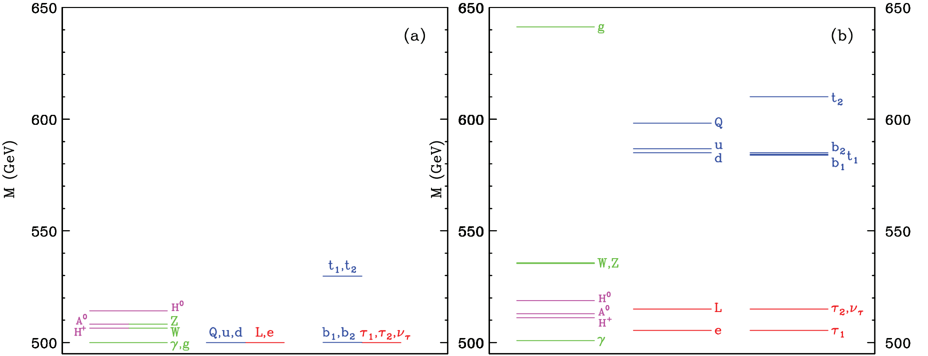


Events / GeV
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1500
3000
4500
6000
7500
Dilepton mass
γ + Z
γ
Z

Universal extra dimensions (UED) : Mass spectrum

Radiative corrections ⇒ mass shifts that lift degeneracy at lowest KK level

divergent sum over KK modes in the loop ⇒ cutoff scale $\Lambda \simeq 10/R$



UED hadron collider phenomenology

- large rates for KK-quark and KK-gluon production
- cascade decays via KK-W bosons and KK-leptons

  determine particle properties from different distributions

- missing energy from LKP: weakly interacting escaping detection
- phenomenology similar to supersymmetry

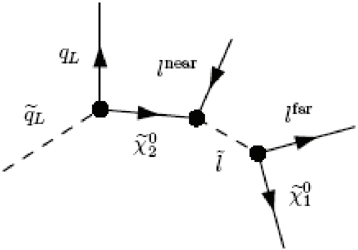
  spin determination important for distinguishing SUSY and UED [40]

gluino	1/2	KK-gluon	1
squark	0	KK-quark	1/2
chargino	1/2	KK-W boson	1
slepton	0	KK-lepton	1/2
neutralino	1/2	KK-Z boson	1

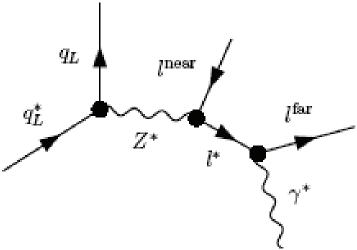
SUSY vs UED signals at LHC

Example: jet dilepton final state

SUSY



UED



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

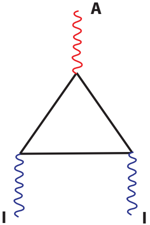
- 4d anomalous $U(1)$'s: $M_A \simeq g_A M_s$

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

or massless in the absence of such anomalies

Green-Schwarz anomaly cancellation



$= k_I^A \sim \mathrm{Tr}\, Q_A Q_I^2 \;\rightarrow$ axion θ : $\delta A = d\Lambda \quad \delta\theta = -m_A \Lambda$

$$-\frac{1}{4g_I^2} F_I^2 - \frac{1}{2}(d\theta + m_A A)^2 + \frac{\theta}{m_A} k_I^A \,\mathrm{Tr}\, F_I \wedge F_I$$

cancel the anomaly

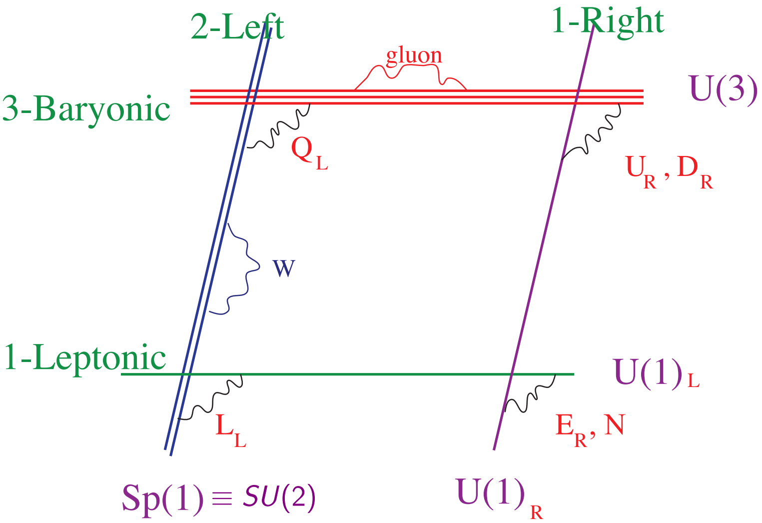
D-brane models: $U(1)_A$ gauge boson acquires a mass

but global symmetry remains in perturbation theory

GS anomaly cancellation $\Rightarrow$ extra scalars and axion-like particles (ALP)

- coupled to gauge kinetic terms
- lighter than the string scale (masses loop-factor suppressed)

Standard Model on D-branes : SM^{++}



$U(1)^3 \Rightarrow$ hypercharge + B, L [28]

global symmetries

- B and L become massive due to anomalies

  Green-Schwarz terms

- the global symmetries remain in perturbation

  - Baryon number $\Rrightarrow$ proton stability

  - Lepton number $\Rrightarrow$ protect small neutrino masses

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

  $\sim$ GeV

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

Exotic $U(1)$ anomaly induced couplings

I.A.-Boyarsky-Ruchayskiy '06, '07

Non trivial anomaly cancellation $\rightarrow$ new **dimensionless** couplings

mixed $U(1)$ anomalies

$\Rightarrow Z'$ may couple to SM gauge bosons with no mass suppression

$$A \wedge X \wedge F_X \qquad A \equiv Z'\,,\ X \equiv W, Y$$

2 axionic phases: $A \rightarrow \theta_A$, $X \rightarrow \theta_X$ $\equiv$ SM Higgs $\Rightarrow$

$$D\theta_A \wedge D\theta_X \wedge F_X \rightarrow \quad \mathcal{L}_{\text{eff}} = c_1 D\theta_A \frac{H^\dagger DH}{|H|^2} F_Y + c_2 D\theta_A \frac{HF_W DH^\dagger}{|H|^2}$$

D'Hoker-Farhi type terms

$$c_2 \rightarrow AW^+W^- \qquad c_1 \rightarrow AZY \quad (AZ\gamma, AZZ) \quad \text{vertices}$$

$$\Gamma(Z' \to ZZ) = \frac{c_1^2 \sin^2\theta_W M_{Z'}^3}{192\pi M_Z^2}\left(1 - \frac{4M_Z^2}{M_{Z'}^2}\right)^{5/2}$$

$$\Gamma(Z' \to W^+W^-) = \frac{c_2^2 M_{Z'}^3}{48\pi M_W^2}\left(1 - \frac{4M_W^2}{M_{Z'}^2}\right)^{5/2}$$

$$\Gamma(Z' \to Z\gamma) = \frac{c_1^2 \cos^2\theta_W M_{Z'}^3}{96\pi M_Z^2}\left(1 - \frac{M_Z^2}{M_{Z'}^2}\right)^3\left(1 + \frac{M_Z^2}{M_{Z'}^2}\right)$$

microgravity experiments

- change of Newton's law at short distances

  detectable only in the case of two large extra dimensions

- new short range forces

  light scalars and gauge fields if SUSY in the bulk

  or broken by the compactification on the brane

  I.A.-Dimopoulos-Dvali '98, I.A.-Benakli-Maillard-Laugier '02

  such as radion and lepton number

  volume suppressed mass: $(\mathrm{TeV})^2/M_P \sim 10^{-4}$ eV $\rightarrow$ mm range

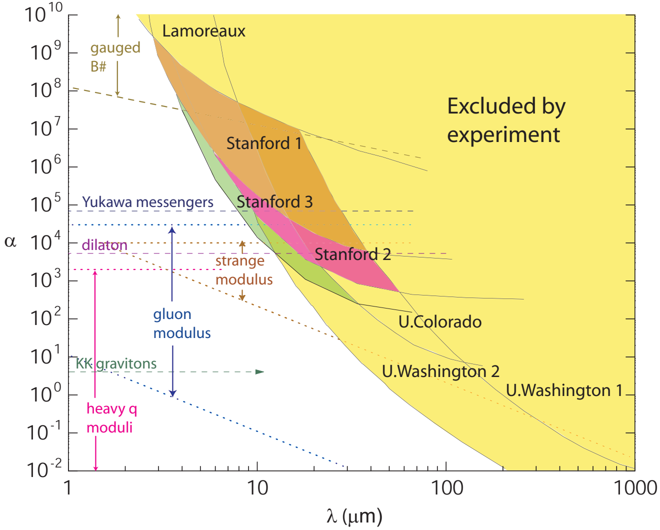
  can be experimentally tested for any number of extra dimensions

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

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

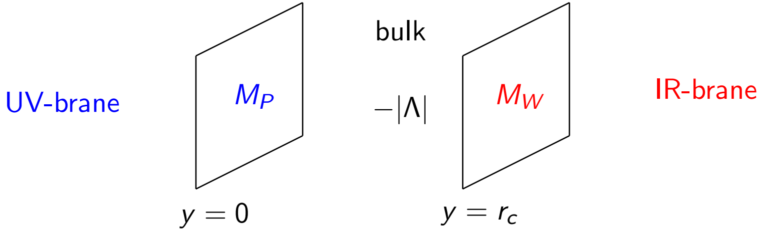
Experimental limits on short distance forces

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



Randal Sundrum models

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



- fine-tuned tensions: $T = -T' = 24M_5^3 k$ [64]
- exponential hierarchy: $M_W = M_P e^{-2kr_c} \qquad M_P^2 \sim M_5^3/k$

$M_5 \sim M_{GUT}$

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

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

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

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

- weakly coupled for $m_n < M_5\, e^{-2kr_c} \qquad \Rightarrow k < M_5$
- viable models: SM gauge bosons in the bulk, Higgs on the IR-brane
- AdS/CFT duals to strongly coupled 4d field theories

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

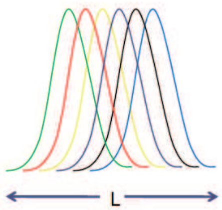
More general framework: large number of species

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 $E \gtrsim N/L \rightarrow$

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 !

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

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

- Large extra dimensions SM on D-branes

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

- $M_s \sim TeV \Rightarrow$ low inflation scale

  allowed by the data since cosmological observables are dimensionless

  in units of the effective gravity scale

I.A.-Patil '14

Cosmological observables

Power spectrum of temperature anisotropies

(adiabatic curvature perturbations $\mathcal{R}$)

$$\mathcal{P}_{\mathcal{R}} = \frac{H^2}{8\pi^2 M_*^2 \epsilon} \simeq \mathcal{A} \times 10^{-10} \quad ; \quad \mathcal{A} \approx 22$$

ϵ: $-\dot{H}/H^2$

Power spectrum of primordial tensor anisotropies $\mathcal{P}_t = 2\dfrac{H^2}{\pi^2 M_*^2}$

$\Rightarrow$ tensor to scalar ratio $r = \mathcal{P}_t/\mathcal{P}_{\mathcal{R}} = 16\epsilon$

measurement of $\mathcal{A}$ and $r \Rightarrow$ fix the scale of inflation

$$H \text{ in terms of } M_* \quad : \quad \frac{H}{M_*} = \left(\frac{\pi^2 \mathcal{A}\, r}{2 \times 10^{10}}\right)^{1/2} \equiv \Upsilon \approx 1.05\sqrt{r} \times 10^{-4}$$

- M_* **may be different than** M_{Planck} **at the time of inflation**

Effective Planck mass and the scale of inflation

I.A.-Patil '14, '15

Explicit realisation:

Flat extra dimensions: obstruction due to the de Sitter bound:

$$M^2_{\mathrm{spin}\,2} \geq 2H^2 \qquad \mathrm{Higuchi}'87$$

$\Rightarrow$ no KK-excitations with mass less than Hubble scale

Kleban-Mirbabayi-Porrati '15

A brane-world model

I.A.-Patil '15 and in preparation

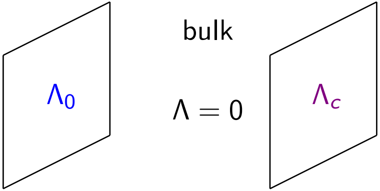
5D brane-world realisation: empty bulk with two boundary dS branes [58]

$$ds^2 = \frac{(1 - H|y|)^2}{H^2\tau^2}\left(-d\tau^2 + dx_1^2 + dx_2^2 + dx_3^2\right) + dy^2$$

$|y| < 1/H$: avoid Riddler horizon $\qquad a(y) = 1 - H|y| > 0$

dS brane

$H = \kappa_5^2 \Lambda_0 / 6$



$y = 0$ $\qquad$ $y = y_c$

dS brane

$H_c = \frac{H}{a_c}\,;\ \Lambda_c = -\frac{\Lambda_0}{a_c}$

$|y_c| = \frac{6(\Lambda_0 + \Lambda_c)}{\kappa_5^2 \Lambda_0 \Lambda_c}$

spectrum and couplings

4d Planck mass: $M_{Pl}^2 \sim 2/(H\kappa_5^2)$ $\quad y_c$ large

Spectrum:

0-mode (4d graviton): wave function $\phi_0 \sim (H/2)^{1/2} e^{-2z}$ $z \equiv -\ln a(y) > 0$

KK-modes: $m_n^2 = H_y^2 \left(\frac{9}{4} + \pi^2 \frac{n^2}{z_c^2}\right)$ $\quad H_y \equiv H/a(y)$: Hubble constant at y

wave functions $\phi_n \sim \frac{H}{2m_n}\left(\frac{H}{z_c}\right)^{1/2} e^{-z/2}\left[3\sin\left(\frac{n\pi z}{z_c}\right) - \frac{2\pi n}{z_c}\cos\left(\frac{n\pi z}{z_c}\right)\right]$

$\Rightarrow$ KK-modes couple much stronger than 0-mode at y_c:

$$|\phi_n|/|\phi_0| = \sqrt{2}\frac{\pi n}{z_c^{3/2}}\frac{H_c}{m_n}\, e^{3z_c/2}$$

similar result for bulk scalars

Power spectrum

0-mode as before:

$$\mathcal{P}_0 = \frac{2}{\pi^2}\frac{H_c^2}{M_{Pl}^2}$$

KK-modes:

$$\mathcal{P}_n = \mathcal{P}_0 \frac{2\pi^2 n^2}{z_c^3} e^{3z_c} \left(\frac{H_c}{m_n}\right)^3 \left(\frac{k}{a_{dS} H_c}\right)^3 \simeq \mathcal{P}_0 \frac{2\pi^2 n^2}{z_c^3} \left(\frac{H_c}{m_n}\right)^3 e^{3(z_c - N)}$$

N: number of e-foldings

Riotto '02

$$\mathcal{P}_0 \lesssim \mathcal{P}_n \Rightarrow e^N \lesssim e^{z_c}/z_c$$

satisfied for TeV scale inflation ($N \gtrsim 35,\ H_c \sim M_5 \sim \mathrm{TeV}$)

Power spectrum

$$\mathcal{P}_{\rm KK} = \sum_n^{m_n < M_5} \mathcal{P}_n = \mathcal{P}_0\, e^{3(z_c - N)}\, \frac{2}{\pi} \ln \frac{M_5 z_c}{\pi H_c}$$

$$\gtrsim \mathcal{P}_0 \;\Rightarrow\; N \lesssim z_c$$

Allowed range of parameters:

$$M_{Pl}^2 \simeq \frac{M_5^3}{H_c} e^{z_c} \Rightarrow e^{z_c} \simeq \frac{M_{Pl}^2 H_c}{M_5^3} \lesssim \frac{M_{Pl}^2}{M_5^2} \qquad H_c < M_5$$

$$e^{N_{\rm min}} = 10^{13} \times \frac{H_c}{1\,{\rm GeV}} \lesssim e^{z_c}$$

$\Rightarrow$ 1 TeV $\lesssim H_c < M_5 \lesssim 10^8$ GeV

Conclusions

String theory has many appealing properties:

- it provides a consistent quantization of gravity
- it gives a framework of unification of all interactions
- it inspired most of BSM new ideas
- it also inspired new results in mathematics
- it is a tool for strong coupling dynamics
- it has spectacular predictions if its scale is accessible to accelerators

It remains to be seen if it is a Theory of Nature