

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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- *String theory in a nutshell*
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Published in Cambridge, UK: Univ. Pr. (2012) 673 p

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 $\rightarrow M_{\text{Planck}} \simeq 10^{15} \times$ the LHC energy!

Newton's law

$$m \bullet \xleftarrow{r} m \quad F_{\text{grav}} = G_N \frac{m^2}{r^2} \quad G_N^{-1/2} = M_{\text{Planck}} = 10^{19} \text{ GeV}$$

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

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

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

\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): ($\text{leptons} + \text{quarks}$) $\times 3$
 - electron, positron, neutrino (up, down) 3 colors
 - ③ Higgs sector: new scalar(s) particle(s)

Electroweak symmetry : spontaneously broken

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

↑
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

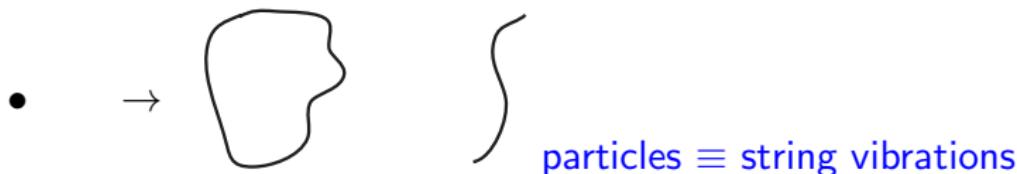
Its discovery was one of the main goals of LHC

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 $\text{EW/gravity} \sim 10^{32}$
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 → extended objects



- quantum gravity
- framework of unification of all interactions
- “ultimate” theory:
 - ultraviolet finite
 - no free parameters

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

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:

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

experimental limits on their size

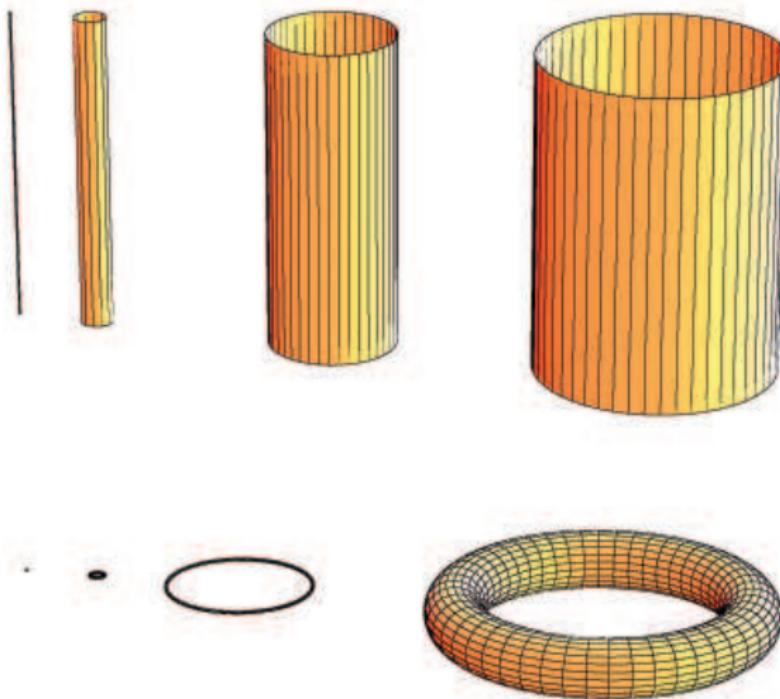
light signal $\Rightarrow E \gtrsim 1 \text{ TeV}$

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

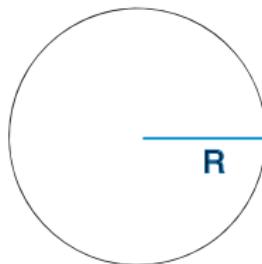
how to detect their existence?

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 $y \rightarrow y + 2\pi R$

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

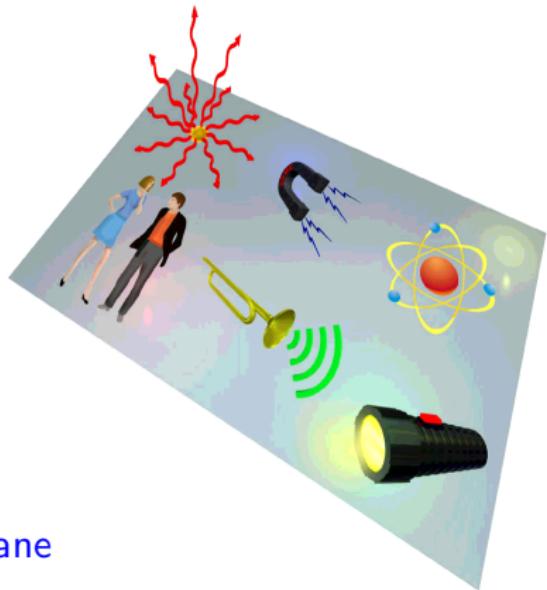
\Rightarrow 3d: tower of Kaluza Klein particles with masses $M_n = n/R$

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

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

\Leftrightarrow propagation in the internal space [10]

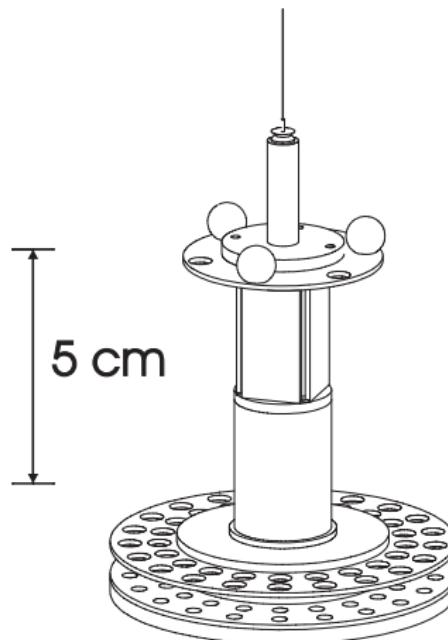
Our universe on a membrane



Two types of new dimensions:

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

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



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

- dark-energy length scale $\approx 85 \mu\text{m}$

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 $(10^{-12}$ GeV) possible

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

$$G_N^* E^{2+n} = G_N E^2 \times V_{\perp} E^n$$

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

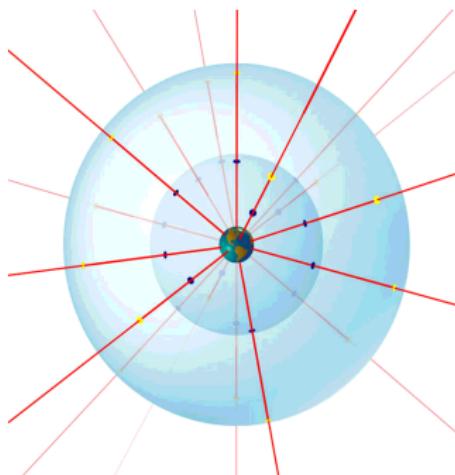
total force $\simeq \mathcal{O}(1)$ at 1 TeV n dimensions of size R_{\perp}

$$\Rightarrow V_{\perp} = R_{\perp}^n$$

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

Gravity modification at submillimeter distances

Newton's law: force decreases with area



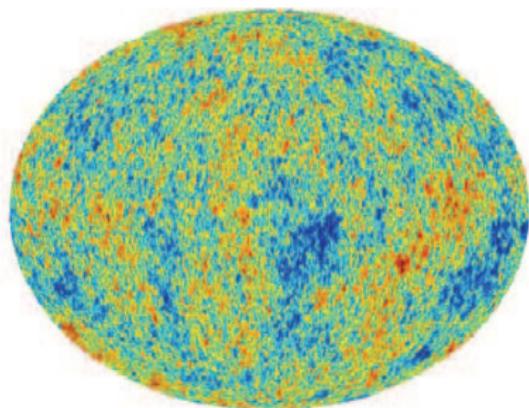
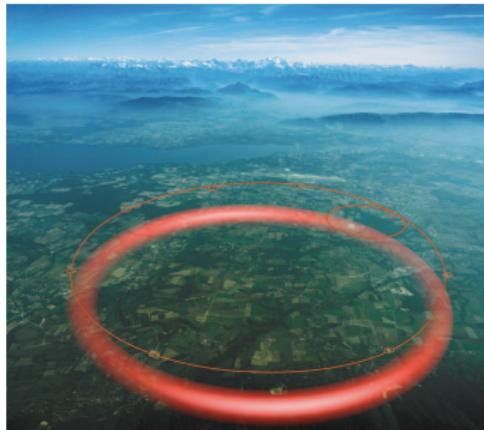
$$3d: \text{force} \sim 1/r^2$$

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

observable for $n = 2$: $1/r^4$ with $r \ll .1 \text{ mm}$ [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?



At what energies strings may be observed?

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

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

- arbitrary parameter : Planck mass $M_P \longrightarrow \text{TeV}$
- physical motivations \Rightarrow favored energy regions:

- High :
$$\begin{cases} M_P^* \simeq 10^{18} \text{ GeV} & \text{Heterotic scale} \\ M_{\text{GUT}} \simeq 10^{16} \text{ GeV} & \text{Unification scale} \end{cases}$$
- Intermediate : around 10^{11} GeV ($M_s^2/M_P \sim \text{TeV}$)
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:

$$M_s = g_H M_P \simeq 50 M_{\text{GUT}} \quad g_H^2 \simeq \alpha_{\text{GUT}} \simeq 1/25 \quad [35]$$

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

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

but loose predictivity [24]

Heterotic string

gravity + gauge kinetic terms [36]

$$\int [d^{10}x] \frac{1}{g_H^2} M_H^8 \mathcal{R}^{(10)} + \int [d^{10}x] \frac{1}{g_H^2} M_H^6 \mathcal{F}_{MN}^2 \quad \text{simplified units: } 2 = \pi = 1$$

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

$$\int [d^4x] \frac{V_6}{g_H^2} M_H^8 \mathcal{R}^{(4)} + \int [d^4x] \frac{V_6}{g_H^2} M_H^6 \mathcal{F}_{\mu\nu}^2$$

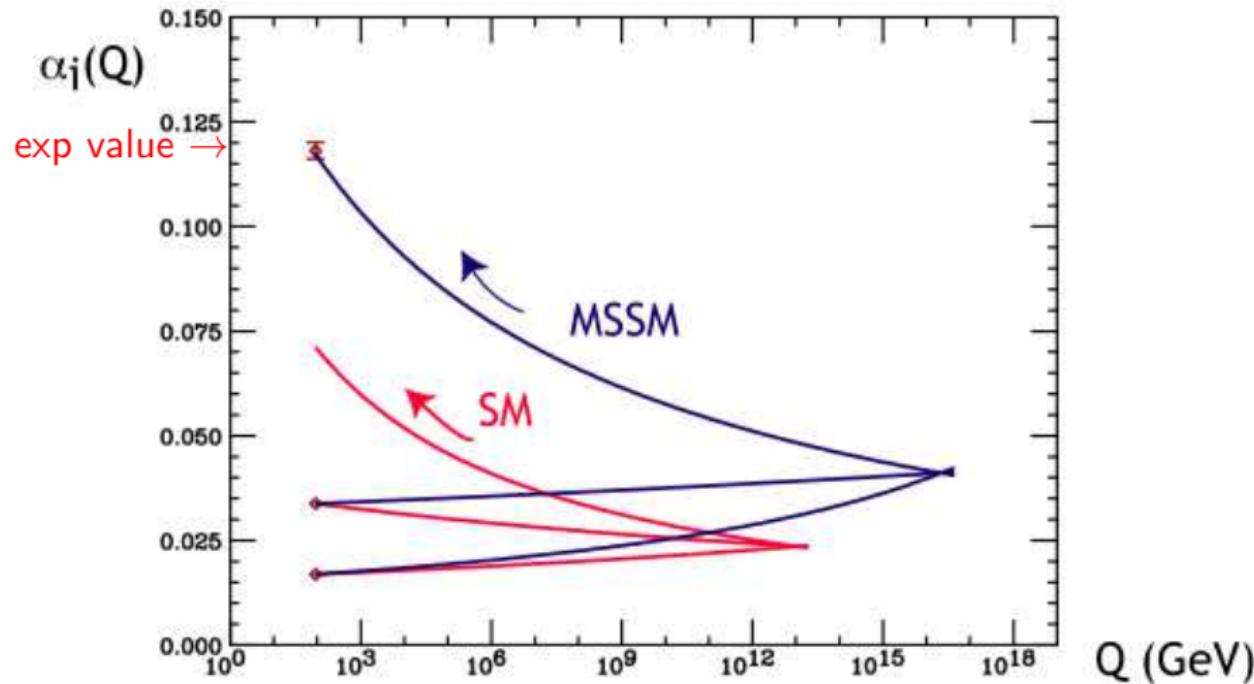
$\begin{array}{c} || \\ M_P^2 \end{array} \qquad \qquad \begin{array}{c} || \\ 1/g^2 \end{array} \qquad \Rightarrow$

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

$$g_H \lesssim 1 \Rightarrow V_6 \sim \text{string size}$$

GUT prediction of QCD coupling

input $\alpha_{\text{em}}, \sin^2 \theta_W \Rightarrow$ output α_3 [36]



Heterotic string: Spectrum

Gauge group $G \leftrightarrow$ affine current algebra in the R-movers (bosonic) CFT

$$[J_n^a, J_m^b] = f^{abc} J_{n+m}^c + k_G \delta^{ab} \delta_{n+m} \quad k_G : \text{integer level of central extension}$$

- $g_G^2 = g_H^2/k_G$
 - dims of allowed matter reps constrained by k_G
- $\Rightarrow k_G = 1 :$
- simplest constructions (CY's, orbifolds, lattices, free fermions)
 - maximum rank: 22
 - guarantee gauge coupling unification at M_H
 - allowed reps: fundamentals & 2-index antisym of unitary groups,
spinors of orthogonal groups

However: - no adjoints to break GUT groups

- in SM $\sin^2 \theta_W = 3/8 \Rightarrow$ fractional electric charges

Schellekens '90

(Hyper)charge quantization

All color singlet states have integer charges

fractional electric charged states: nice prediction or problematic?

lightest is stable \Rightarrow problematic?

ways out: - superheavy + inflate away

- be confined to integrally charged by extra gauge group

live without adjoints \Rightarrow non conventional ‘semi’-GUTs

e.g. break fictitious $SO(10)$ by discrete Wilson lines or projection to

flipped $SU(5) \times U(1)$, Pati-Salam type $SU(4) \times SU(2)_L \times SU(2)_R$, or direct SM

Heterotic models revived: Orbifold GUTs

groups in Munich, Bonn, Hamburg, Ohio, U Penn

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 $\Rightarrow \sigma$: 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

D p -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

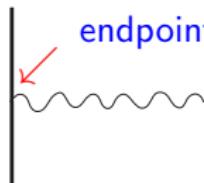
$X^\mu = X_0^\mu$ at $\sigma = 0$ ($\partial_\tau X^\mu = 0$ at $\sigma = 0$)

Dirichlet conditions: endpoint fixed at the boundary

D-brane spectrum

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

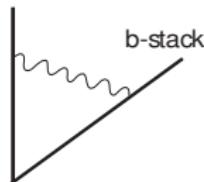
a-stack



endpoint transformation: N_a or \bar{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 $U(N_a) \times U(N_b)$

a-stack



non-oriented strings \Rightarrow also:

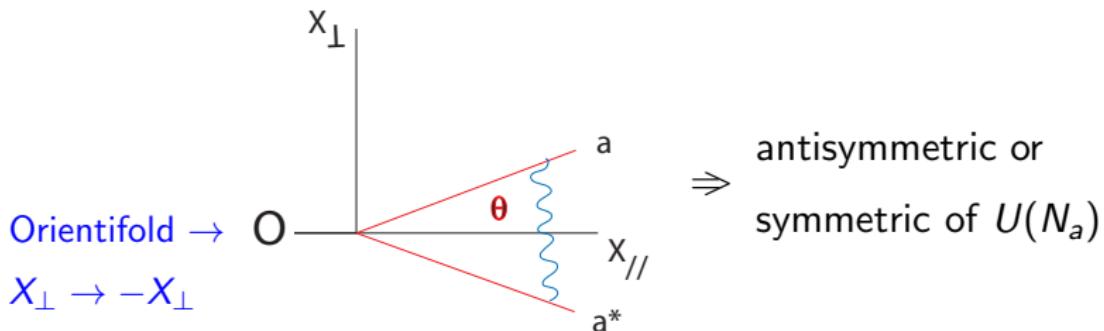
- orthogonal and symplectic groups $SO(N), Sp(N)$
- matter in antisymmetric + symmetric reps

Non oriented strings \Rightarrow orientifold planes

where closed strings change orientation

\Rightarrow mirror branes identified with branes under orientifold action

- strings stretched between two mirror stacks



Minimal Standard Model embedding

General analysis using 3 brane stacks [53]

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

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

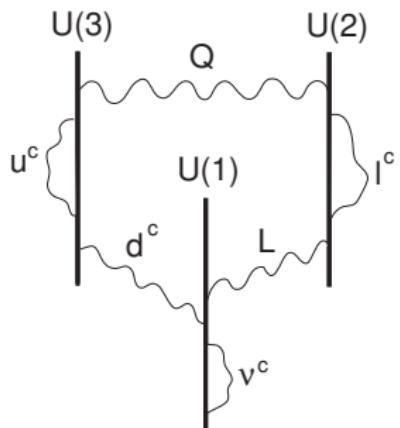
N_i stack of D-branes: $U(N_i) = SU(N_i) \times U(1)_i$

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

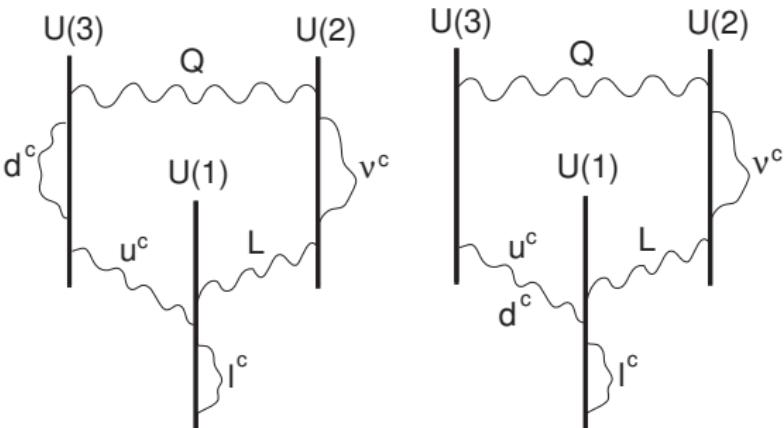
normalization: $\text{Tr } T^a T^b = \frac{1}{2} \delta^{ab} \Rightarrow \alpha_i = \frac{\alpha_{N_i}}{2N_i}$

$$Y = c_1 Q_1 + \textcolor{red}{c}_2 Q_2 + \textcolor{blue}{c}_3 Q_3 \Rightarrow \frac{1}{g_Y^2} = \frac{2c_1^2}{g_1^2} + \frac{4c_2^2}{g_2^2} + \frac{6c_3^2}{g_3^2}$$

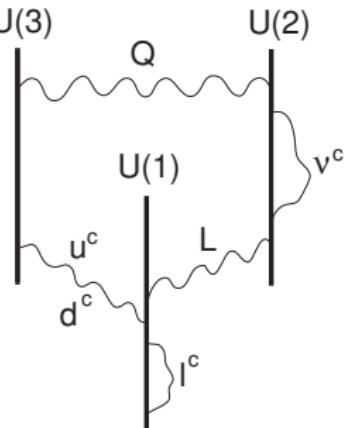
$$\sin^2 \theta_W = \frac{g_Y^2}{g_2^2 + g_Y^2} = \frac{1}{g_2^2/g_Y^2 + 1} = \frac{1}{1 + 4c_2^2 + 2c_1^2 g_2^2/g_1^2 + 6c_3^2 g_2^2/g_3^2}$$



Model A

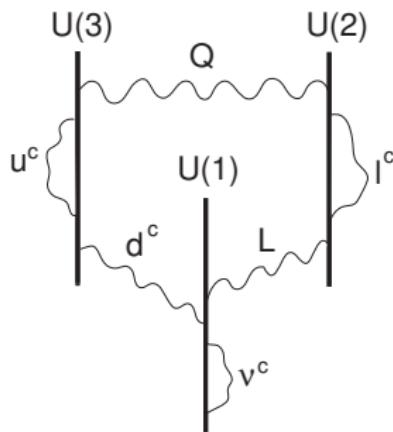


Model B

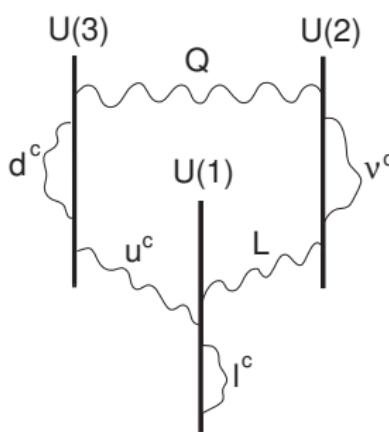


Model C

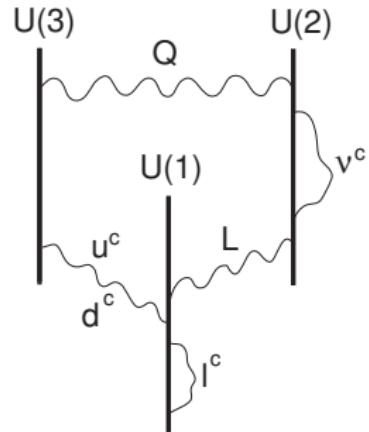
Q	$(\mathbf{3}, \mathbf{2}; 1, 1, 0)_{1/6}$	$(\mathbf{3}, \mathbf{2}; 1, \varepsilon_Q, 0)_{1/6}$	$(\mathbf{3}, \mathbf{2}; 1, \varepsilon_Q, 0)_{1/6}$
u^c	$(\bar{\mathbf{3}}, \mathbf{1}; 2, 0, 0)_{-2/3}$	$(\bar{\mathbf{3}}, \mathbf{1}; -1, 0, 1)_{-2/3}$	$(\bar{\mathbf{3}}, \mathbf{1}; -1, 0, 1)_{-2/3}$
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

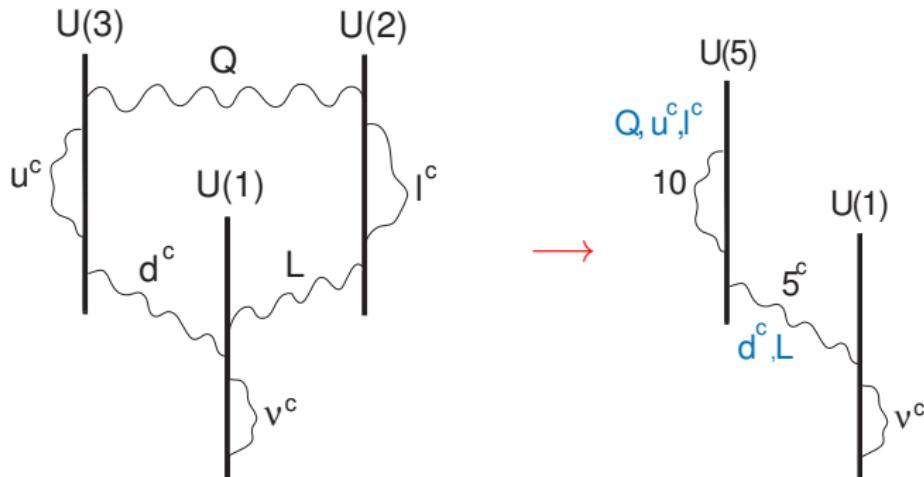
$$Y_A = -\frac{1}{3}Q_3 + \frac{1}{2}Q_2$$

$$Y_{B,C} = \frac{1}{6}Q_3 - \frac{1}{2}Q_1$$

$$\sin^2 \theta_W = \frac{1}{2 + 2\alpha_2/3\alpha_3} \Big|_{\alpha_2=\alpha_3} = \frac{3}{8}$$

$$\frac{1}{1 + \alpha_2/2\alpha_1 + \alpha_2/6\alpha_3} \Big|_{\alpha_2=\alpha_3} = \frac{6}{7 + 3\alpha_2/\alpha_1}$$

$SU(5)$ 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 ...

→ 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 [37]

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

$$M_p^2 \simeq \frac{1}{g_s^2} M_s^{2+n} R_{\perp}^n \quad g_s = \alpha : \text{weak string coupling}$$

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

$$M_s \sim 1 \text{ TeV} \Rightarrow R_{\perp}^n = 10^{32} l_s^n \quad \text{small } M_s/M_P \Rightarrow \text{extra-large } R_{\perp}$$

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

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

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

gravity + gauge kinetic terms

$$\int [d^{10}x] \frac{1}{g_s^2} M_s^8 \mathcal{R}^{(10)} + \int [d^{p+1}x] \frac{1}{g_s} M_s^{p-3} \mathcal{F}_{MN}^2 \quad [22]$$

Compactification in 4 dims \Rightarrow

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

$$M_P^2 \quad \quad \quad 1/g^2 \quad \Rightarrow$$

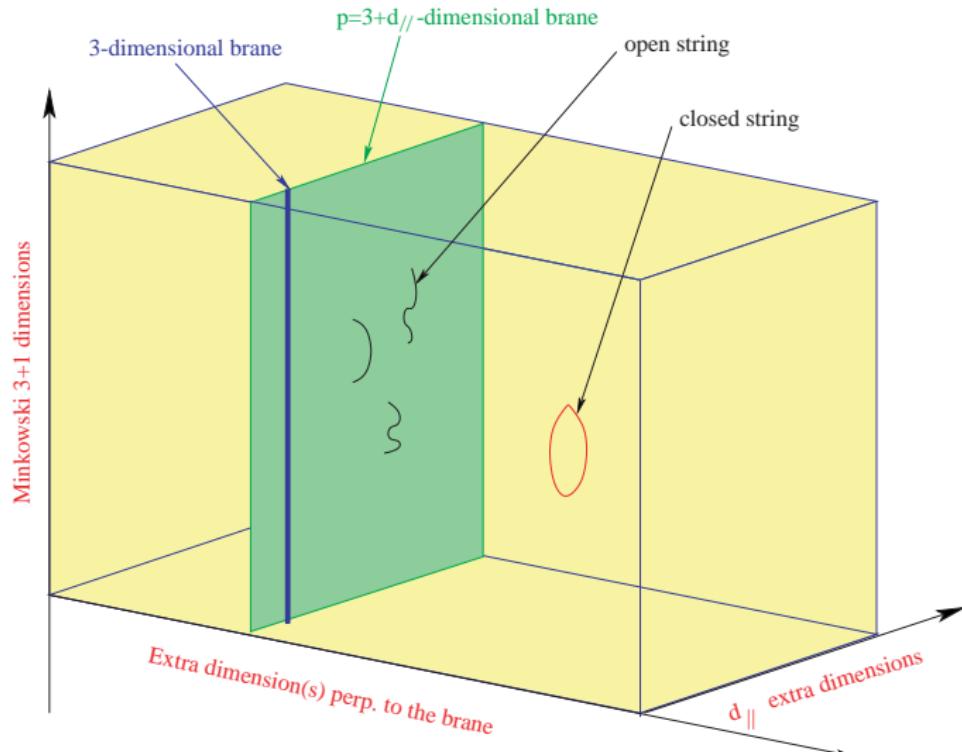
$$g_s = g^2 V_{\parallel} M_s^{p-3} \lesssim 1 \Rightarrow V_{\parallel} \sim \text{string size}$$

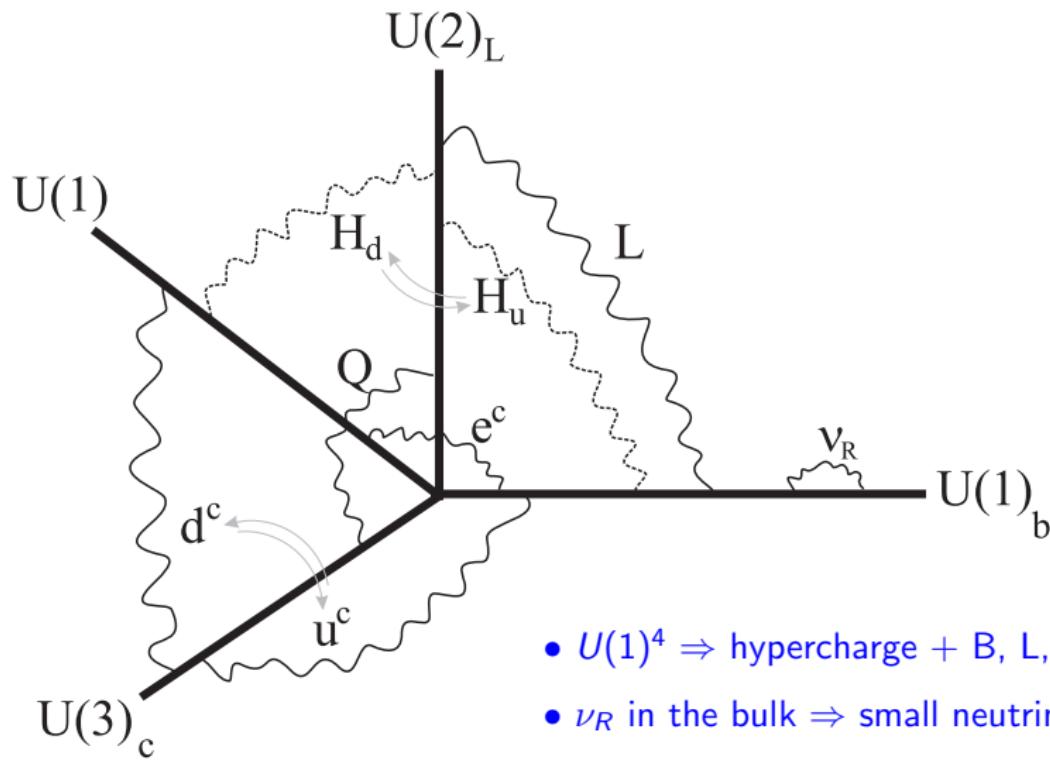
$$\Rightarrow M_P^2 = \frac{V_\perp}{g_s^2} M_s^{2+n} \quad g_s \simeq g^2$$

Braneworld

2 types of compact extra dimensions:

- parallel (d_{\parallel}): $\lesssim 10^{-16}$ cm (TeV) [35]
- transverse (\perp): $\lesssim 0.1$ mm (meV)





- $U(1)^4 \Rightarrow$ 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: $\nu_R(x, \textcolor{blue}{y})$ y : bulk coordinates

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

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

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

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

$$m_\nu \ll 1/R_\perp \Rightarrow \text{KK modes unaffected}$$

Experimental predictions

- No little hierarchy problem:
 - radiative electroweak symmetry breaking with no logs
 - $\Lambda \sim \text{a few TeV}$ and $m_H^2 = \text{a loop factor} \times \Lambda^2$
- 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

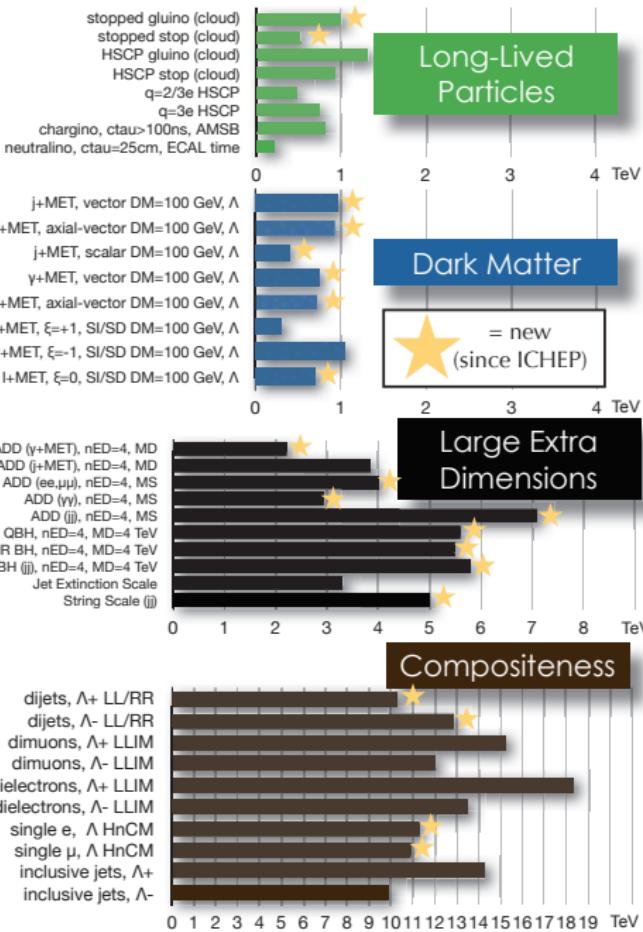
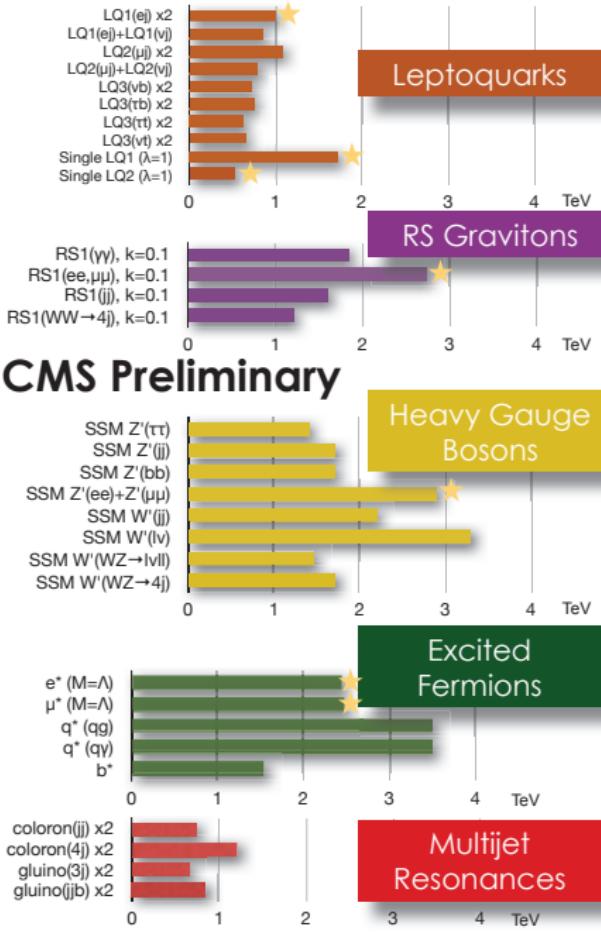
Accelerator signatures: 4 different scales

- Gravitational radiation in the bulk \Rightarrow missing energy
present LHC bounds: $M_* \gtrsim 3 - 7 \text{ TeV}$
- 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
present LHC limits: $M_s \gtrsim 5 \text{ TeV}$
- Large TeV dimensions \Rightarrow KK resonances of SM gauge bosons I.A. '90
$$M_k^2 = M_0^2 + k^2/R^2 \quad ; \quad k = \pm 1, \pm 2, \dots$$

experimental limits: $R^{-1} \gtrsim 0.5 - 4 \text{ TeV}$ (UED - localized fermions) [46]
- extra $U(1)$'s and anomaly induced terms
masses suppressed by a loop factor from M_s [51]

CMS Preliminary



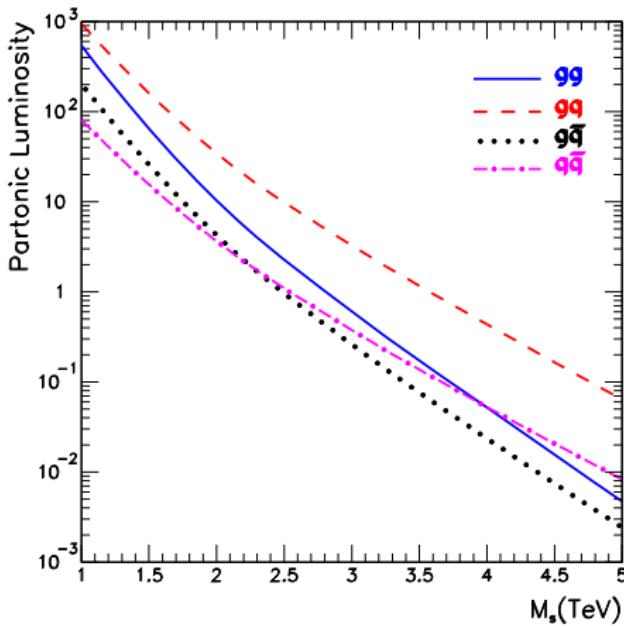
Tree level superstring amplitudes involving at most 2 fermions and gluons:
model independent for any compactification, # of susy's, even none
no intermediate exchange of KK, windings or graviton emmission
Universal sum over infinite exchange of string (Regge) excitations

Parton luminosities in pp above TeV

are dominated by gq, gg

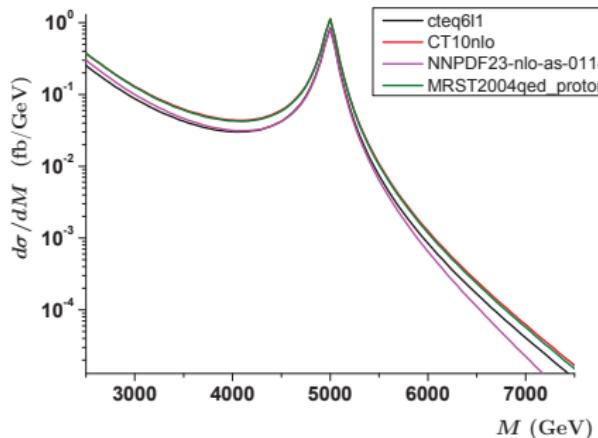
⇒ model independent

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

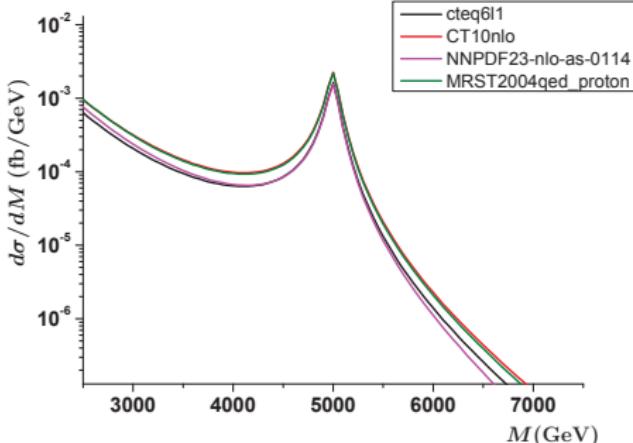


String Resonances production at Hadron Colliders

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



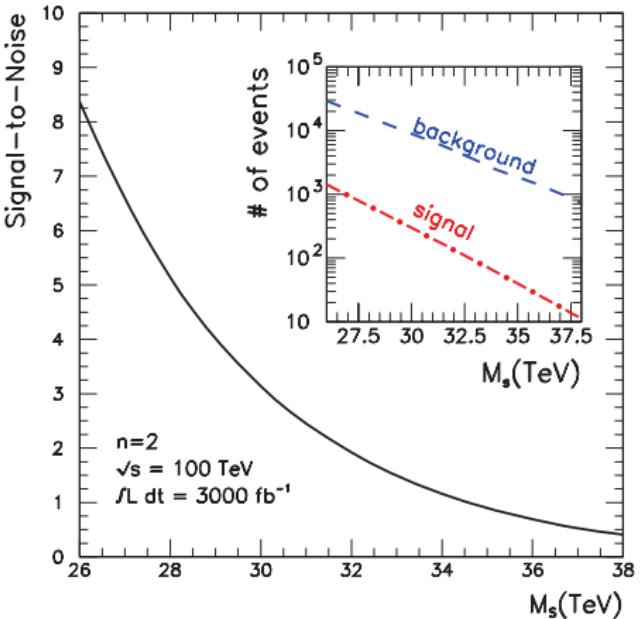
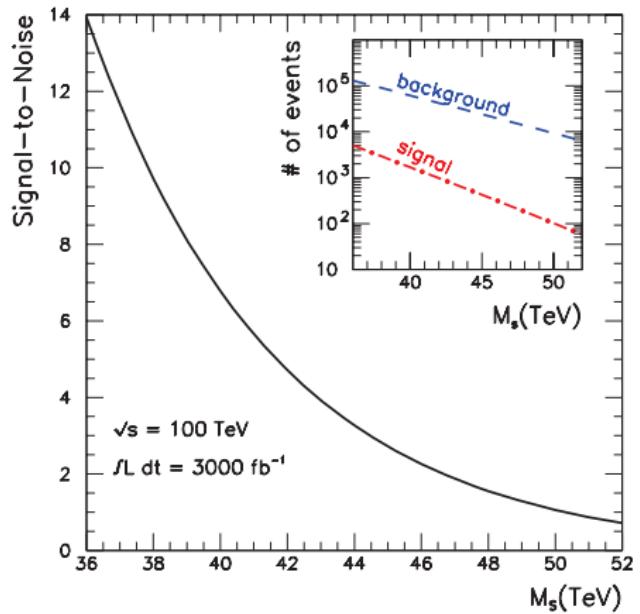
$M_s = 5$ TeV: dijet at LHC14



$\gamma +$ jet

String Resonances production at Hadron Colliders

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

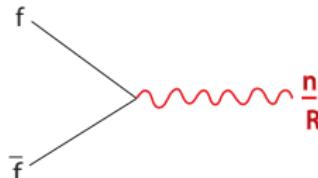


[41]

Localized fermions (on 3-brane intersections)

⇒ single production of KK modes

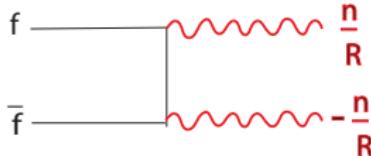
I.A.-Benakli '94



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

Otherwise KK momentum conservation [48]

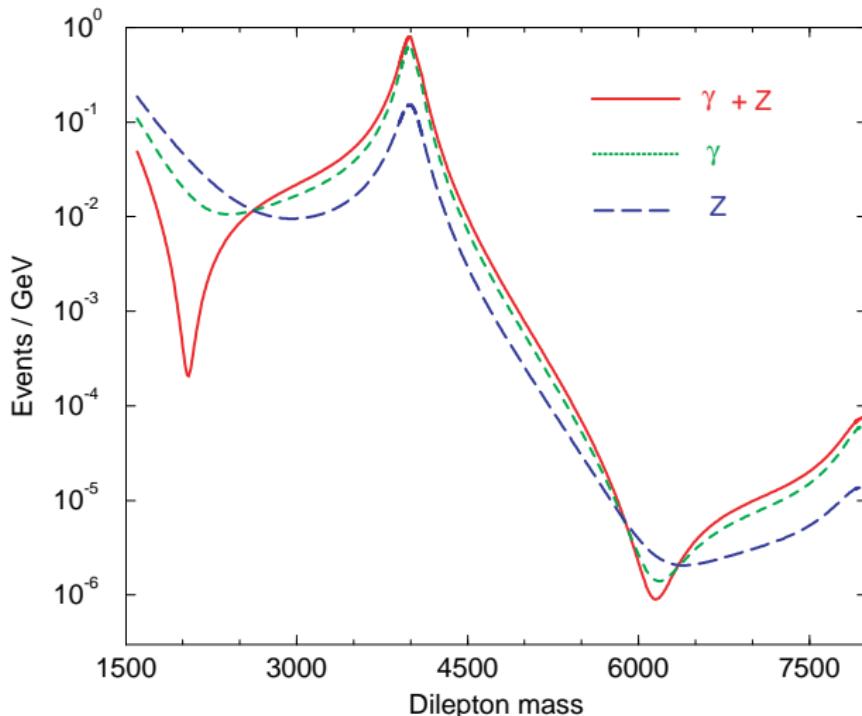
⇒ pair production of KK modes (universal dims)



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

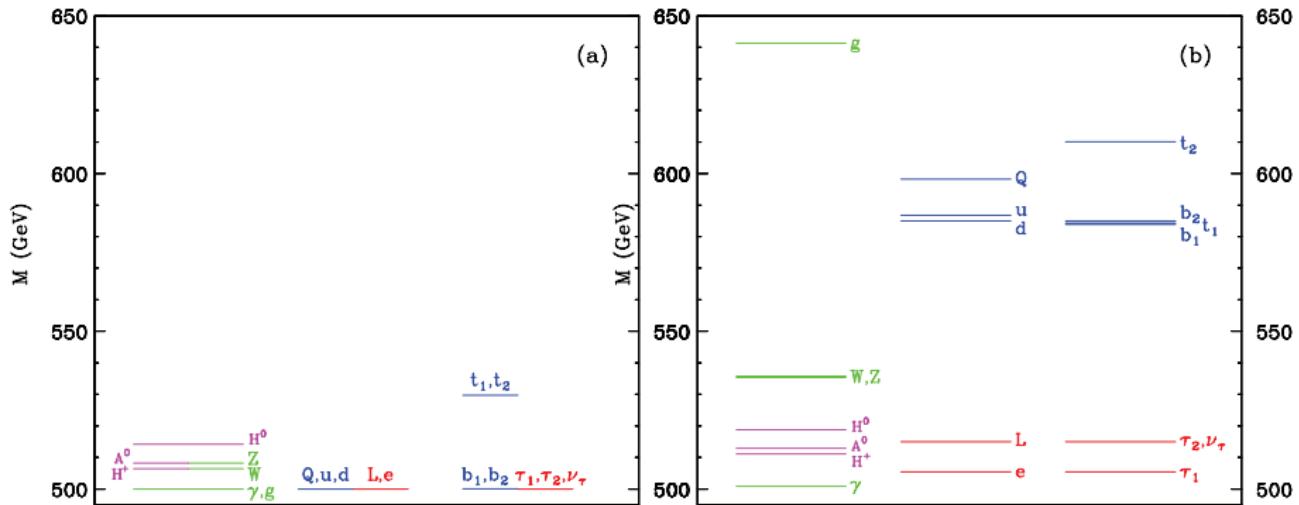
Servant-Tait '02

$$R^{-1} = 4 \text{ TeV}$$



Universal extra dimensions (UED) : Mass spectrum

Radiative corrections \Rightarrow mass shifts that lift degeneracy at lowest KK level
divergent sum over KK modes in the loop \Rightarrow cutoff scale $\Lambda \simeq 10/R$



UED hadron collider phenomenology

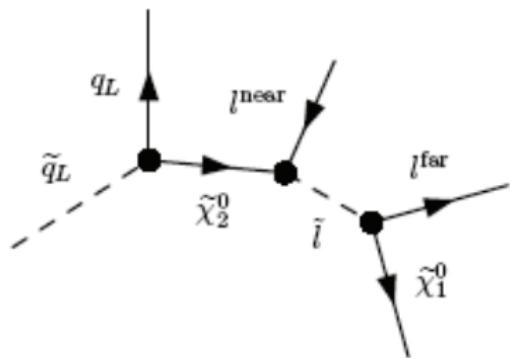
- large rates for KK-quark and KK-gluon production
- cascade decays via KK- W bosons and KK-leptons
 - determine particle properties from different distributions
- missing energy from LKP: weakly interacting escaping detection
- phenomenology similar to supersymmetry
 - spin determination important for distinguishing SUSY and UED [41]

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

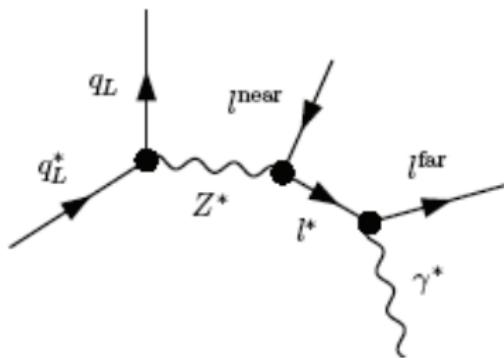
SUSY vs UED signals at LHC

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

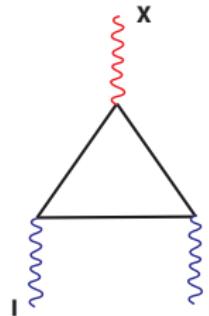
- 4d anomalous $U(1)$'s: $M_A \simeq g_A M_s$

- 4d non-anomalous $U(1)$'s: (but masses related to 6d anomalies)

$$M_{NA} \simeq g_A M_s V_2 \leftarrow (6d \rightarrow 4d) \text{ internal space} \Rightarrow M_{NA} \geq M_A$$

or massless in the absence of such anomalies

Green-Schwarz anomaly cancellation


$$= k_I^A \sim \text{Tr} Q_A Q_I^2 \rightarrow \text{axion } \theta : \delta A = d\Lambda \quad \delta\theta = -m_A \Lambda$$
$$-\frac{1}{4g_I^2} F_I^2 - \frac{1}{2} (d\theta + m_A A)^2 + \frac{\theta}{m_A} k_I^A \text{Tr} F_I \wedge F_I$$

cancel the anomaly

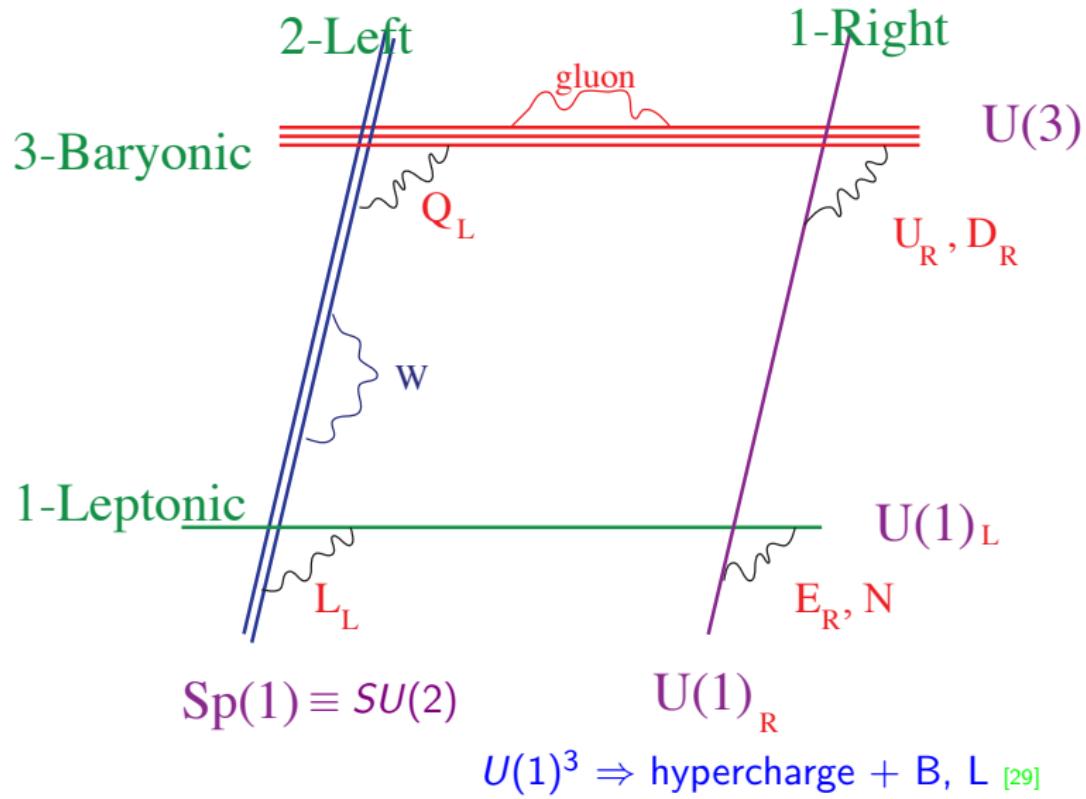
string theory: $\theta = \text{Poincaré dual of a 2-form}$ $d\theta = *dB_2$

Heterotic: single universal axion

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

but global symmetry remains in perturbation theory

Standard Model on D-branes : SM⁺⁺



global symmetries

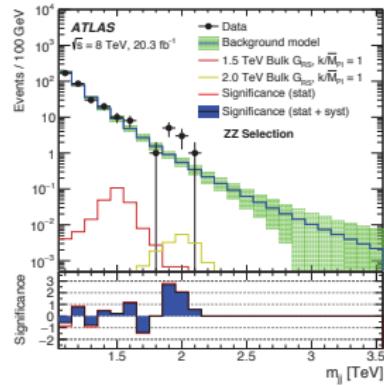
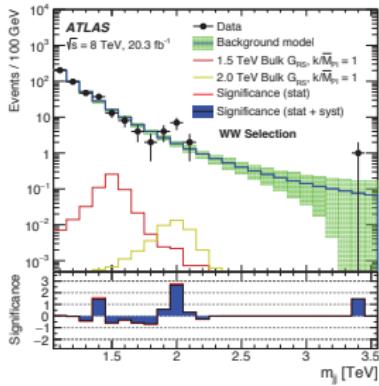
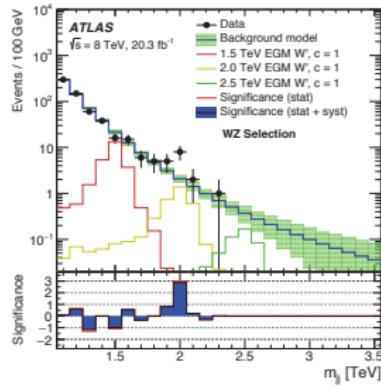
- B and L become massive due to anomalies
Green-Schwarz terms
- the global symmetries remain in perturbation
 - Baryon number \Rightarrow proton stability
 - Lepton number \Rightarrow protect small neutrino masses
- no Lepton number $\Rightarrow \frac{1}{M_s} LLHH \rightarrow$ Majorana mass: $\frac{\langle H \rangle^2}{M_s} LL$

 $\sim \text{GeV}$
- $B, L \Rightarrow$ extra Z' 's
with possible leptophobic couplings leading to CDF-type Wjj events

$$Z' \simeq B \text{ lighter than } 4\text{d anomaly free } Z'' \simeq B - L$$

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

Diboson and dijet excesses at LHC around 2 TeV



similar for CMS

possible explanation:

a Z' decaying into W, Z but with suppressed couplings to fermions

Anchordoqui-I.A.-Goldberg-Huang-Lüst-Taylor '15

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

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

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

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

D'Hoker-Farhi type terms

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

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

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

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

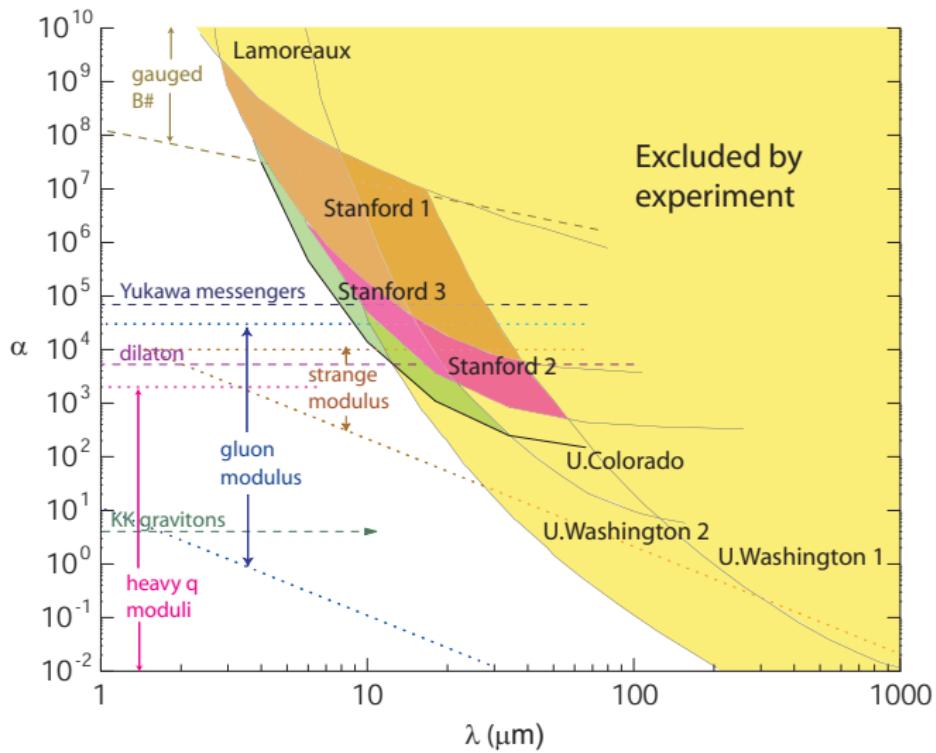
Fit data with $c_1 \simeq 0.08$ and $c_2 \simeq 0.02$

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: $(\text{TeV})^2/M_P \sim 10^{-4} \text{ eV} \rightarrow \text{mm range}$
- can be experimentally tested for any number of extra dimensions
- Light $U(1)$ gauge bosons: no derivative couplings
 - ⇒ for the same mass much stronger than gravity: $\gtrsim 10^6$

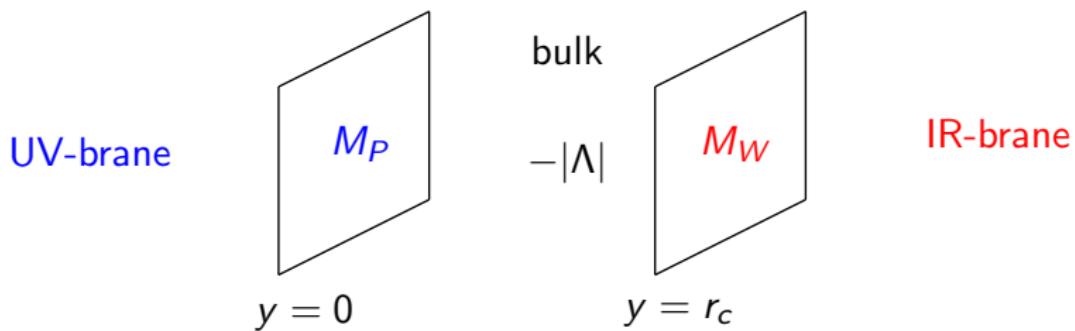
Experimental limits on short distance forces

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



Randal Sundrum models

spacetime = slice of AdS₅ : $ds^2 = e^{-2k|y|} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2$ $k^2 \sim \Lambda/M_5^3$



- fine-tuned tensions: $T = -T' = 24M_5^3 k$
- 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

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

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

⇒ spin-2 TeV resonances in di-lepton or di-jet channels

- weakly coupled for $m_n < M_5 e^{-2kr_c}$ $\Rightarrow k < M_5$
- 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 $g_{YM} = M_5/k > 1$

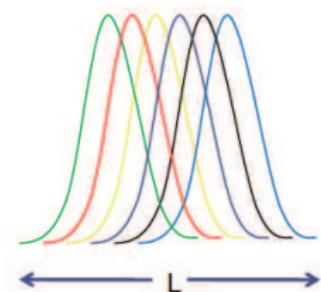
More general framework: large number of species

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 : $L \gtrsim R_s \Rightarrow L \gtrsim \sqrt{N}/M_p = 1/M_*$

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

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

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

- Large extra dimensions SM on D-branes

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

- $M_s \sim \text{TeV} \Rightarrow$ 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})

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

$\downarrow -\dot{H}/H^2$

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

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

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

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

Extra species as Kaluza-Klein states

$D = 4 + n$ extra dims of size average size $R \Rightarrow$

$$\text{fundamental gravity scale } M_s^{2+n} R^n = M_{Pl}^2$$

$N = \text{all KK states with mass less than } H \Rightarrow N \simeq (HR)^n$

$$M_* = M_{Pl}/\sqrt{N} = M_s(M_s R)^{n/2}/(HR)^{n/2} = M_s(M_s/H)^{n/2}$$

$$H = M_* \Upsilon = M_s(M_s/H)^{n/2} \Upsilon \quad \Rightarrow \quad H = M_s \Upsilon^{2/(n+2)}$$

$\Rightarrow H \sim 1\text{-}3 \text{ orders of magnitude less than } M_s$ for $0.001 \lesssim r \lesssim 0.1$

as low as near the EW scale

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