# An introduction to string phenomenology

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# Outline

1. String phenomenology: what for? 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
6. Warped spaces and holography

# Bibliography

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  Ignatios Antoniadis, Guillaume Ovarlez
  e-Print: hep-th/9906108
- *Topics on String Phenomenology*
  I. Antoniadis
  e-Print: arXiv:0710.4267 [hep-th]
- *String theory in a nutshell*
  E. Kiritsis
  Princeton University Press, 2007
- *String theory and particle physics: An introduction to string phenomenology*
  Luis E. Ibanez, Angel M. Uranga
  Published in Cambridge, UK: Univ. Pr. (2012) 673 p

# Fundamental interactions

| force | range | intensity of 2 protons | intensity at $10^{-16}$ cm |
|---|---|---|---|
| Gravitation | $\infty$ | $10^{-38}$ | $10^{-30}$ |
| Electromagnetic | $\infty$ | $10^{-2}$ | $10^{-2}$ |
| Weak<br>(radioactivity $\beta$) | $10^{-15}$ cm | $10^{-5}$ | $10^{-2}$ |
| Strong<br>(nuclear forces) | $10^{-12}$ cm | 1 | $10^{-1}$ |

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

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

# Newton's law

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

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 $E$

$E = m_{\rm proton} \ \Rightarrow \ \frac{F_{\rm grav}}{F_{\rm el}} = \frac{G_N m_{\rm proton}^2}{e^2} \simeq 10^{-40}$ [19]

$\Rightarrow$ Gravity is very weak !

Weak Gravity Conjecture: it is the weakest force in Nature

$\Rightarrow$ minimal non-trivial charge $e \geq m$ in Planck units

Arkani-Hamed, Motl, Nicolis, Vafa '06

# 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) × 3

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

# Electroweak symmetry : spontaneously broken

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

$\nwarrow$ observed at LEP

a new particle is needed : Higgs boson (scalar)

- break the EW symmetry at ~ 250 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 in 2012 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 $\Rightarrow$

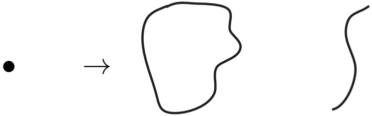
  fine-tuning of parameters in 32 decimal places!

- neutrino masses and oscillations

- origin of Dark Matter in the Universe

# String theory: Quantum Mechanics + General Relativity

point particle → extended objects



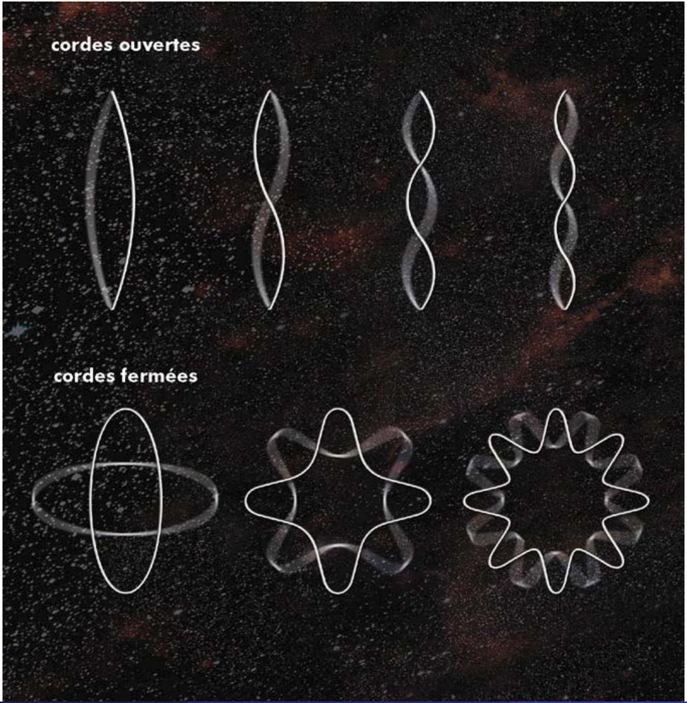
particles $\equiv$ string vibrations

- 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


cordes ouvertes
cordes fermées

# Strings and extra dimensions

Consistent theory $\Rightarrow$ 9 spatial dimensions ! (10 in M-theory)

**six new dimensions of space**

matter and gauge interactions may be localized

in less than 9 dimensions $\Rrightarrow$

**our universe on a membrane ?** [15]

$p$-plane: extended in $p$ spatial dimensions

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

# Extra Dimensions

Kaluza and Klein 1920

**how they escape observation?**

finite size $R$

energy cost to send a signal:

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

**experimental limits on their size**

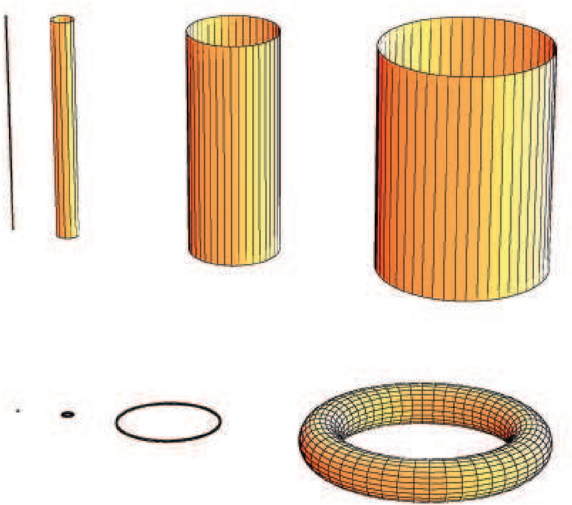
light signal $\Rightarrow \quad E \gtrsim 1$ TeV

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

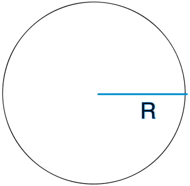
**how to detect their existence?**

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 $y \to y + 2\pi R$

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

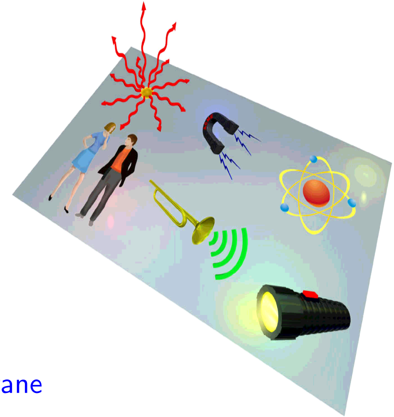
$\Rightarrow$ 3d: tower of Kaluza Klein particles with masses $M_n = |n|/R$

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

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

$\Leftrightarrow$ propagation in the internal space [11]

# Our universe on a membrane

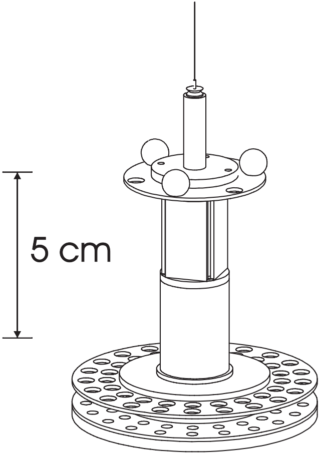


Two types of new dimensions:

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

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

Adelberger et al. ’06



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

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

Relativistic dark energy 70-75% of the observable universe

negative pressure: $p = -\rho$ $\Rightarrow$ cosmological constant

$$R_{ab} - \frac{1}{2} R g_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4} T_{ab} \;\Rightarrow\; \rho_\Lambda = \frac{c^4 \Lambda}{8\pi G} = -p_\Lambda$$

Two length scales:

- $[\Lambda] = L^{-2} \leftarrow$ size of the observable Universe

  $\Lambda_{obs} \simeq 0.74 \times 3H_0^2/c^2 \simeq 1.4 \times (10^{26}\,\mathrm{m})^{-2}$

  $\nwarrow$ Hubble parameter $\simeq 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

- $[\frac{\Lambda}{G} \times \frac{c^3}{\hbar}] = L^{-4} \leftarrow$ dark energy length $\simeq 85\mu\mathrm{m}$

# 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 [20]

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

$10^{30}$ times stronger than thought previously! [22]

# Low scale gravity

Extra large ⊥ dimensions can explain the apparent weakness of gravity

total force = observed force × volume ⊥ [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

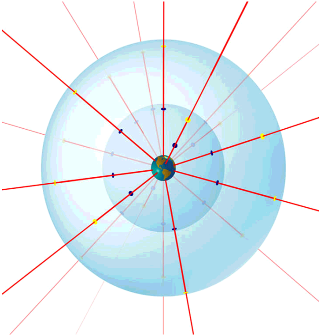
$n$ dimensions of size $R_\perp$

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

$\Rightarrow M_P^2 = M_*^{2+n} R_\perp^n$ 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 [18]

# Gravity modification at submillimeter distances

Gradual change of force behaviour at short distances

Exchange of a massive particle ⇛ Yukawa potential

$$V_m = \frac{e^{-mr}}{r}$$

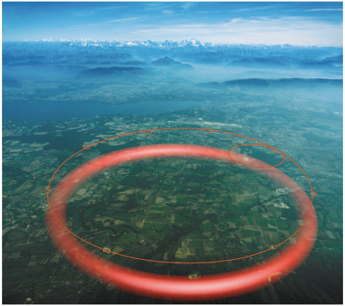
Sum over exchange of KK modes with masses $|n|/R$, $n = 0, \pm 1, \pm 2, \ldots$ :

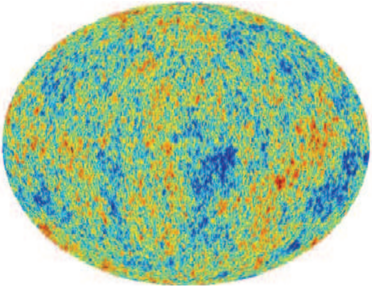
$$\begin{aligned} V &= \frac{1}{r}\left(1 + 2e^{-r/R} + 2e^{-2r/R} + \ldots\right) \\ &= \frac{1}{r}\left(1 + \frac{2}{e^{r/R} - 1}\right) = \begin{cases} \frac{1}{r} & \text{for } r >> R \\ \\ \frac{2R}{r^2} & \text{for } r << R \end{cases} \end{aligned}$$

$$Q_5 = 2RQ_4$$

# Connect string theory to the real world

- Is it a tool for strong coupling dynamics or a theory of fundamental forces?
- 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

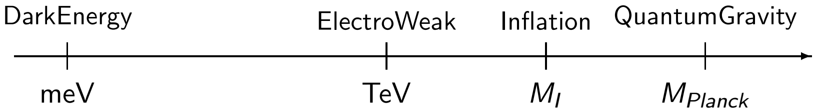
- incorporate Dark Energy

  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 $M_{Planck}$ :



DarkEnergy — meV

ElectroWeak — TeV

Inflation — $M_I$

QuantumGravity — $M_{Planck}$

# 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   $l_s \simeq 10^{-32}$ cm   After 1998:

- 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 : (multi) 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:

$M_s = g\,M_P \simeq 50\,M_{\rm GUT}$ $\qquad g^2 \simeq \alpha_{\rm GUT} \simeq 1/25$ [46]

in GUTs only one prediction from 3 gauge couplings unification: $\sin^2\theta_W$ [27]

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

but loose predictivity [28]

# Heterotic string

gravity + gauge kinetic terms [47]

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

simplified units: $2 = \pi = 1$

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

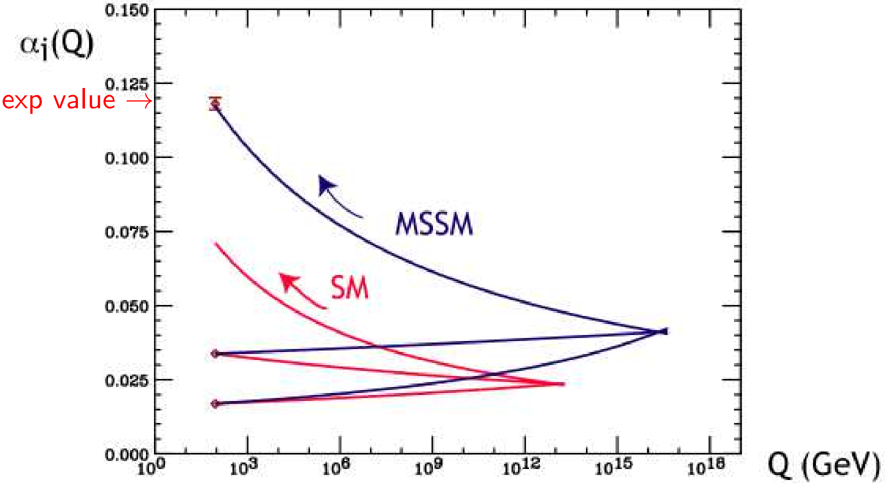
$$\int [d^4x]\, \underbrace{\frac{V_6}{g_H^2} M_H^8}_{M_P^2}\, \mathcal{R}^{(4)} + \int [d^4x]\, \underbrace{\frac{V_6}{g_H^2} M_H^6}_{1/g^2}\, \mathcal{F}_{\mu\nu}^2 \qquad \Rightarrow$$

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

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

# GUT prediction of QCD coupling

input $\alpha_{\rm em}, \sin^2\theta_W$ $\Rightarrow$ output $\alpha_3$ [25] [47]



# Heterotic string: Spectrum

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

$$\left[J^a_n, J^b_m\right] = f^{abc} J^c_{n+m} + k_G\, \delta^{ab} \delta_{n+m} \quad k_G \text{ : integer level of central extension}$$

$$\left.\begin{array}{l} \cdot \quad g_G^2 = g_H^2/k_G \\ \cdot \quad \text{dims of allowed matter reps constrained by } k_G \end{array}\right\} \Rightarrow k_G = 1 :$$

- 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 $\Rrightarrow$ problematic?

ways out: - superheavy + inflate away

- be confined to integrally charged by extra gauge group

live without adjoints $\Rrightarrow$ 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

# Flipped $SU(5)$: explicit string construction

IA-Ellis-Haggelin-Nanopoulos '87-'89

Framework: 4d heterotic strings in the 2d free-fermionic formulation

describing the internal (6,22)-dim compactification

with parameters the boundary conditions and corresponding coefficients

IA-Bachas-Kounnas-Windey '86, ABK '86, AB '87; Kawai-Lewellen-Tye '86, '87

**Flipped $SU(5)$: minimal variation of $SU(5)$**

**that does not require GUT Higgs adjoints**

explicit string construction with realistic phenomenology [32]

# Flipped $SU(5)$: the model

matter representations: exchange $d^c$ and $u^c$ between $\mathbf{\bar{5}}$ and $\mathbf{10}$ $\Rightarrow$

$\mathbf{\bar{5}_{\bar{f}}} = (u^c, l)$, $\mathbf{10_F} = [Q, d^c, \nu^c]$, $l^c$, extra $U(1)$: $SU(5) \times U(1)$

Higgs representations: $10_H + \overline{10}_{\bar{H}}$, $5_h + \bar{5}_{\bar{h}}$

$SU(5) \times U(1) \to SU(3) \times SU(2) \times U(1)$ via $\langle H \rangle = \langle \bar{H} \rangle \neq 0$ along $\nu^c_H, \bar{\nu}^c_{\bar{H}}$

$5_h = (d_h, h_2)$, $\bar{5}_{\bar{h}} = (d^c_h, h_1)$ contain the electroweak higgs $h_1, h_2$

General superpotential invariant under $H \to -H$ in presence of singlets $\phi$

$$W = \lambda_d FFh + \lambda_u F\bar{f}\bar{h} + \lambda_e l^c \bar{f} h + \lambda_4 HHh + \lambda_5 \bar{H}\bar{H}\bar{h} + \lambda_6 F\bar{H}\phi + \lambda_7 h\bar{h}\phi + \lambda_8 \phi^3$$

- $\lambda_4, \lambda_5 \Rightarrow$ doublet-triplet splitting with GUT masses $d_h d^c_H + \bar{d}_{\bar{h}} \bar{d}^c_{\bar{H}}$
- $\lambda_u \Rightarrow m_u = m_\nu$

  however see-saw mechanism with $\nu^c$ and $\phi$ via $\lambda_6$ and $\lambda_8$

- Higgs from untwisted sector ⇛ gauge-Higgs unification

  $\lambda_{\rm top} = g_{\rm GUT} \Rrightarrow m_{\rm top} \sim$ IR fixed point $\simeq 170$ GeV

- Yukawa couplings: hierarchies à la Froggatt-Nielsen

  discrete symmetries ⇛ couplings allowed with powers of a singlet field

  $\lambda_n \sim \Phi^n \qquad \langle\Phi\rangle \sim 0.1\, M_H \to$ hierarchies

  A single anomalous $U(1) \Rrightarrow \langle\Phi\rangle \neq 0$ to cancel the FI D-term

  D-term is shifted to $\mathrm{D} + \frac{\mathrm{Tr}\,Q}{192\pi^2} g_H^2$ [69]

- R-neutrinos: natural framework for see-saw mechanism

  $\langle h\rangle \nu_L \nu_R + M\nu_R\nu_R \qquad \langle h\rangle = v << M \Rrightarrow m_R \sim M\,;\, m_L \sim v^2/M$

- proton decay: problematic dim-5 operators

  in general need suppression higher than $M_H$ or small couplings

- S$\not{U}$SY in a hidden sector from the other $E_8 \to$ gravity mediation

# Open strings and D-branes

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

$\tau$: 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: $X^1, \ldots, X^p$ (also time $X^0$)

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

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

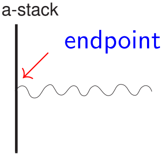
transverse dimensions: $X^{p+1}, \ldots, X^9$

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

Dirichlet conditions: endpoint fixed at the boundary

# D-brane spectrum

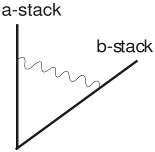
Generic spectrum: $N$ coincident branes $\Rightarrow$ $U(N)$



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

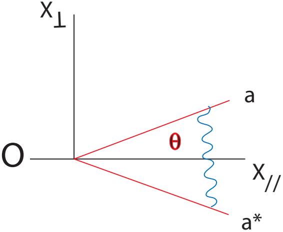
where closed strings change orientation

⇒ 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 [70]

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

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

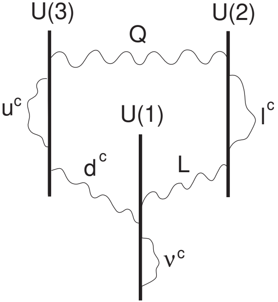
$N_i$ stack of D-branes: $U(N_i) = SU(N_i) \times U(1)_i$

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

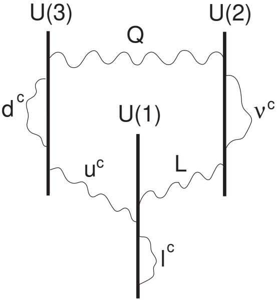
normalization: $\mathrm{Tr}\, T^a T^b = \dfrac{1}{2}\delta^{ab} \;\Rightarrow\; \alpha_i = \dfrac{\alpha_{N_i}}{2N_i}$

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

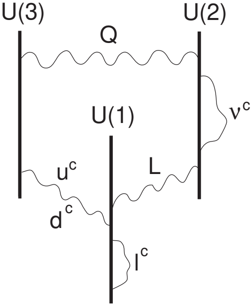
$$\sin^2\theta_W = \frac{g_Y^2}{g_2^2 + g_Y^2} = \frac{1}{g_2^2/g_Y^2 + 1} = \frac{1}{1 + 4c_2^2 + 2c_1^2 g_2^2/g_1^2 + 6c_3^2 g_2^2/g_3^2}$$



**Model A**

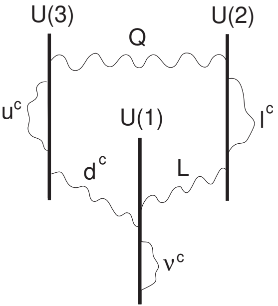


**Model B**

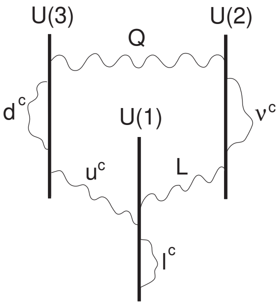


**Model C**

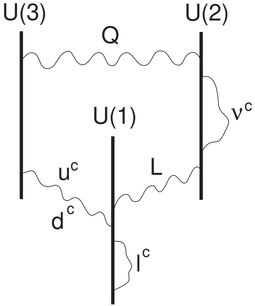
| | | | |
|---|---|---|---|
| $Q$ | $(\mathbf{3},\mathbf{2};1,1,0)_{1/6}$ | $(\mathbf{3},\mathbf{2};1,\varepsilon_Q,0)_{1/6}$ | $(\mathbf{3},\mathbf{2};1,\varepsilon_Q,0)_{1/6}$ |
| $u^c$ | $(\bar{\mathbf{3}},\mathbf{1};2,0,0)_{-2/3}$ | $(\bar{\mathbf{3}},\mathbf{1};-1,0,1)_{-2/3}$ | $(\bar{\mathbf{3}},\mathbf{1};-1,0,1)_{-2/3}$ |
| $d^c$ | $(\bar{\mathbf{3}},\mathbf{1};-1,0,\varepsilon_d)_{1/3}$ | $(\bar{\mathbf{3}},\mathbf{1};2,0,0)_{1/3}$ | $(\bar{\mathbf{3}},\mathbf{1};-1,0,-1)_{1/3}$ |
| $L$ | $(\mathbf{1},\mathbf{2};0,-1,\varepsilon_L)_{-1/2}$ | $(\mathbf{1},\mathbf{2};0,\varepsilon_L,1)_{-1/2}$ | $(\mathbf{1},\mathbf{2};0,\varepsilon_L,1)_{-1/2}$ |
| $l^c$ | $(\mathbf{1},\mathbf{1};0,2,0)_1$ | $(\mathbf{1},\mathbf{1};0,0,-2)_1$ | $(\mathbf{1},\mathbf{1};0,0,-2)_1$ |
| $\nu^c$ | $(\mathbf{1},\mathbf{1};0,0,2\varepsilon_\nu)_0$ | $(\mathbf{1},\mathbf{1};0,2\varepsilon_\nu,0)_0$ | $(\mathbf{1},\mathbf{1};0,2\varepsilon_\nu,0)_0$ |



**Model A**



**Model B**

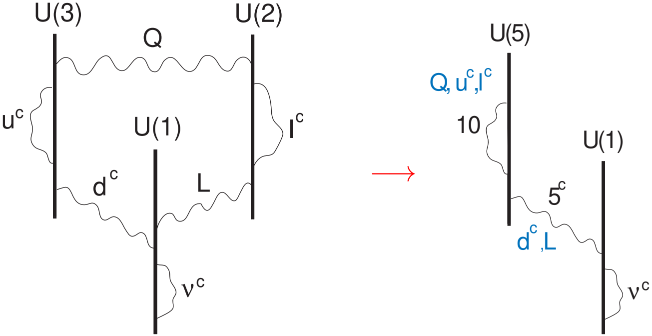


**Model C**

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

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

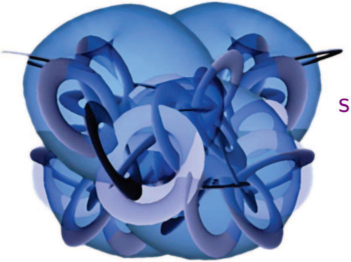
# $SU(5)$ GUT



# String moduli

String compactifications from 10/11 to 4 dims → scalar moduli

arbitrary VEVs: parametrize the compactification manifold



size of cycles, shapes, . . . , string coupling

- $N = 1$ SUSY $\Rrightarrow$ complexification: scalar + i pseudoscalar $\equiv \phi_i$
- Low energy couplings: functions of moduli

e.g. gauge couplings: $\frac{1}{g_a^2} F_a^2$ $a$: gauge group

$N = 1$ SUSY $\Rightarrow$ holomorphicity: $\frac{1}{g_a^2} = \mathrm{Re}\, f_a(\phi_i)$

SUSY transformation $\Rightarrow$ moduli-dependent $\theta$-angles:

$$\theta_a F_a \tilde{F}_a \quad \text{with} \quad \theta_a = \mathrm{Im}\, f_a(\phi_i)$$

In superspace: $\int d^2\theta\, f(\phi_i)\, W_a^2 \leftarrow$ gauge field-strength chiral superfield

# Moduli stabilization

If moduli massless → inconsistent

long range forces, cosmological production, accelerators

Outstanding problem: moduli stabilization

- avoid experimental conflict
- fix their VEVs ⇒ compute low energy couplings

Generate moduli potential:
- preserving SUSY
- after SUSY breaking

via

• non-perturbative effects or by

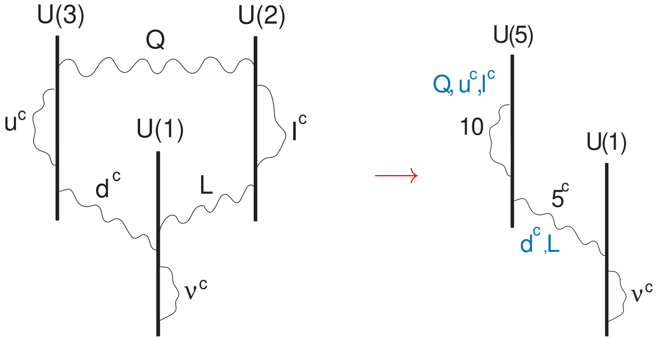
• turn-on fluxes: constant field-strengths of generalized gauge potentials

gauge fields: internal magnetic fields

generalization: higher rank antisymmetric tensors

# Model building with magnetized branes

I.A.-Kumar-Panda '07



Full string embedding with all geometric moduli stabilized:

- all extra $U(1)$'s broken ⇒ gauge group just susy $SU(5)$
- gauge non-singlet chiral spectrum: 3 generations of quarks + leptons
- SUSY can be broken in an extra $U(1)$ factor by D-term

→ gauge mediation

# 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 $\pm 1$

  $\Rightarrow$ 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 [49]

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

$M_p^2 \simeq \frac{1}{g_s^2} M_s^{2+n} R_\perp^n$ $g_s = \alpha$ : weak string coupling [25]

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

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

$M_s \sim 1$ TeV $\Rightarrow R_\perp^n = 10^{32}\ l_s^n$ [74]

$R_\perp \sim .1 - 10^{-13}$ 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

$$\int [d^{10}x]\,\frac{1}{g_s^2}M_s^8\,\mathcal{R}^{(10)} + \int [d^{p+1}x]\,\frac{1}{g_s}M_s^{p-3}\,\mathcal{F}^2_{MN}$$ [26]

Compactification in 4 dims $\Rrightarrow$

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

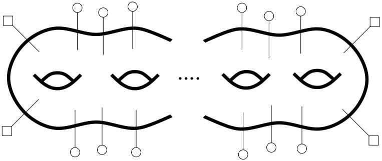
$$\Rrightarrow$$

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

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

string propagation in space-time ⇒ 2-dim world-sheet

string perturbation theory : world-sheet topological expansion



$\sim g_s^{-\chi}$ $\chi$: Euler number

general characterization of 2-dim Riemann surfaces:

$$\chi = 2 - 2\underset{\nearrow}{h} \quad - \quad \underset{\uparrow}{b} \quad - \quad \underset{\nwarrow}{c}$$

genus=nb of handles boundaries (branes) crosscaps (orientifolds)

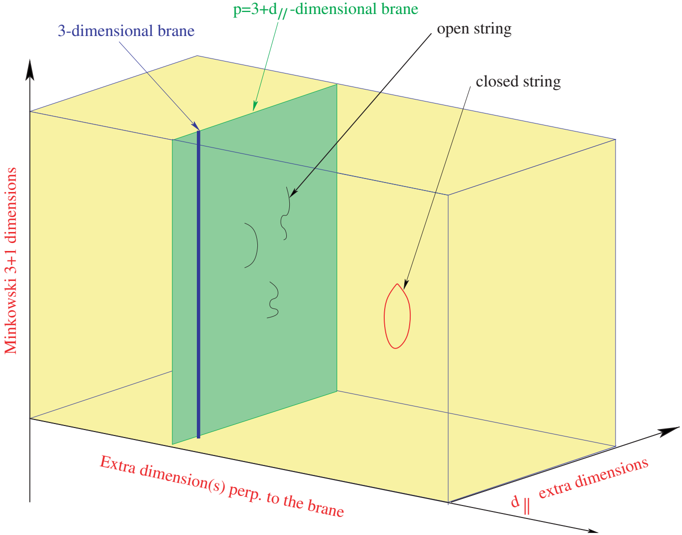
tree-level: $h = b = c = 0 \quad \Rightarrow \quad 1/g_s^2$

“tree-level” open strings: $h = c = 0,\ b = 1 \quad \Rightarrow \quad 1/g_s$

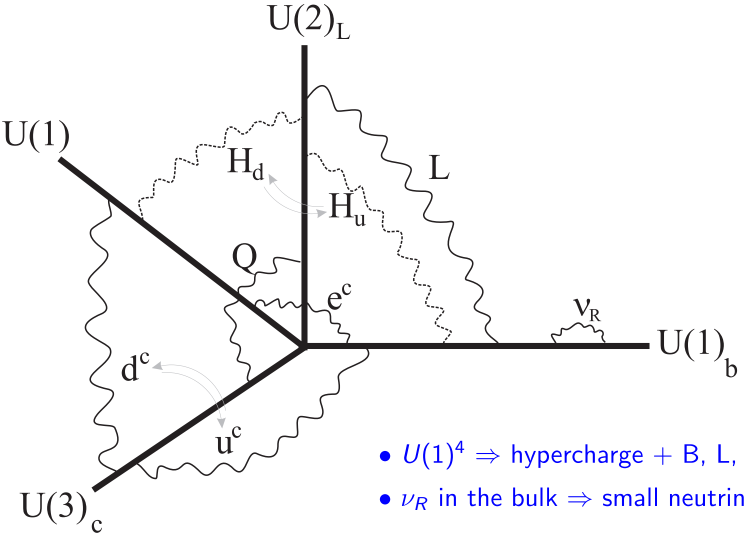
# Braneworld

2 types of compact extra dimensions:

- parallel ($d_\parallel$): $\lesssim 10^{-16}$ cm (TeV) [46]
- 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 [70]
- $\nu_R$ 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 [55]

  - Large TeV dimensions seen by gauge interactions

  - Extra large hidden dimensions transverse ⇒ strong gravity

  - other accelerator signatures

- microgravity experiments [72]

  - gravity modifications at short distances

  - new submillimeter forces

# Origin of EW symmetry breaking?

possible answer: radiative breaking — I.A.-Benakli-Quiros '00

$V = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2$

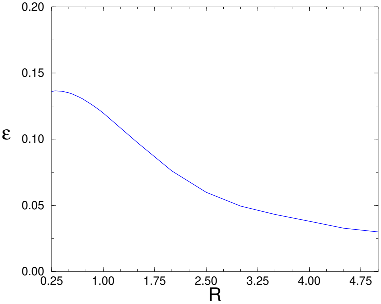
$\mu^2 = 0$ at tree but becomes $< 0$ at one loop — non-susy vacuum

simplest case: one Higgs from the same brane

$\Rightarrow$ tree-level $V$ same as susy: $\lambda = \frac{1}{8}(g_2^2 + g_Y^2)$ — D-terms

$\mu^2 = -g^2 \varepsilon^2 M_s^2 \leftarrow$ effective UV cutoff

$$\varepsilon^2(R) = \frac{R^3}{2\pi^2}\int_{\underset{\text{IR}\nearrow}{0}}^{\overset{\text{UV}\searrow}{\infty}} dl\, l^{3/2}\, \frac{\overset{\nearrow e^{-\pi l}}{\theta_2^4}}{\underset{\searrow 1}{16 l^4 \eta^{12}}} \left(il + \frac{1}{2}\right) \sum_n n^2 e^{-2\pi n^2 R^2 l}$$



$R \to 0$ : $\varepsilon(R) \simeq 0.14$ large transverse dim $R_\perp = l_s^2/R \to \infty$

$R \to \infty$ : $\varepsilon(R) M_s \sim \varepsilon_\infty / R$ $\varepsilon_\infty \simeq 0.008$ UV cutoff: $M_s \to 1/R$

Higgs scalar = component of a higher dimensional gauge field

$\Rightarrow \varepsilon_\infty$ calculable in the effective field theory

$\lambda = g^2/4 \sim 1/8 \quad \Rightarrow \quad M_H \simeq v/2 = 125$ GeV

$M_s$ or $1/R \sim$ a few or several TeV [52]

# Accelerator signatures: 4 different scales

- Gravitational radiation in the bulk ⇛ missing energy [57]

  present LHC bounds: $M_* \gtrsim 3 - 11$ TeV

- Massive string vibrations ⇛ e.g. resonances in dijet distribution [59]

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

  higher spin excitations of quarks and gluons with strong interactions

  present LHC limits: $M_s \gtrsim 8$ 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: $R^{-1} \gtrsim 2 - 6$ TeV (UED - localized fermions) [63]

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

  masses suppressed by a loop factor from $M_s$ [68]

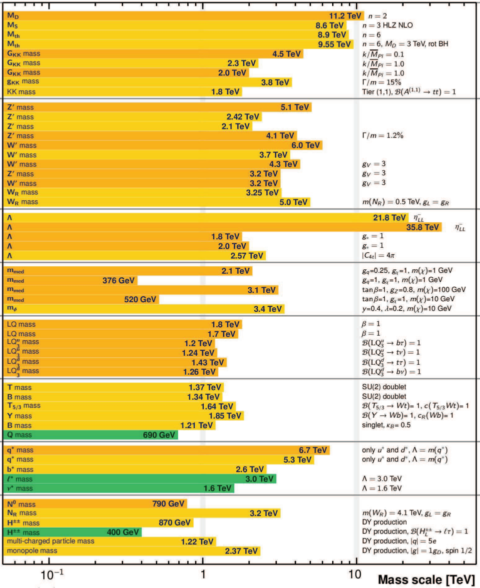
# ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: March 2021

**ATLAS** Preliminary

$\int \mathcal{L}\, dt = (3.6 - 139)\ \mathrm{fb}^{-1}$

$\sqrt{s} = 8, 13$ TeV



| | Model | $\ell, \gamma$ | Jets† | $E_T^{miss}$ | $\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$ | Limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Extra dimensions | ADD $G_{KK} + g/q$ | 0 $e, \mu, \tau, \gamma$ | 1 – 4 j | Yes | 139 | $M_D$ 11.2 TeV | $n = 2$ | 2102.10874 |
| | ADD non-resonant $\gamma\gamma$ | 2 $\gamma$ | – | – | 36.7 | $M_S$ 8.6 TeV | $n = 3$ HLZ NLO | 1707.04147 |
| | ADD QBH | – | 2 j | – | 37.0 | $M_{th}$ 8.9 TeV | $n = 6$ | 1703.09127 |
| | ADD BH multijet | – | ≥ 3 j | – | 3.6 | $M_{th}$ 9.55 TeV | $n = 6$, $M_D = 3$ TeV, rot BH | 1512.02586 |
| | RS1 $G_{KK} \to \gamma\gamma$ | 2 $\gamma$ | – | – | 139 | $G_{KK}$ mass 4.5 TeV | $k/\overline{M}_{Pl} = 0.1$ | 2102.13405 |
| | Bulk RS $G_{KK} \to WW/ZZ$ | multi-channel | | | 36.1 | $G_{KK}$ mass 2.3 TeV | $k/\overline{M}_{Pl} = 1.0$ | 1808.02380 |
| | Bulk RS $G_{KK} \to WV \to \ell\nu qq$ | 1 $e, \mu$ | 2 j / 1 J | Yes | 139 | $G_{KK}$ mass 2.0 TeV | $k/\overline{M}_{Pl} = 1.0$ | 2004.14636 |
| | Bulk RS $g_{KK} \to tt$ | 1 $e, \mu$ | ≥ 1 b, ≥ 1J/2j | Yes | 36.1 | $g_{KK}$ mass 3.8 TeV | $\Gamma/m = 15\%$ | 1804.10823 |
| | 2UED / RPP | 1 $e, \mu$ | ≥ 2 b, ≥ 3 j | Yes | 36.1 | KK mass 1.8 TeV | Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$ | 1803.09678 |
| Gauge bosons | SSM $Z' \to \ell\ell$ | 2 $e, \mu$ | – | – | 139 | $Z'$ mass 5.1 TeV | | 1903.06248 |
| | SSM $Z' \to \tau\tau$ | 2 $\tau$ | – | – | 36.1 | $Z'$ mass 2.42 TeV | | 1709.07242 |
| | Leptophobic $Z' \to bb$ | – | 2 b | – | 36.1 | $Z'$ mass 2.1 TeV | | 1805.09299 |
| | Leptophobic $Z' \to tt$ | 0 $e, \mu$ | ≥ 1 b, ≥ 2 J | Yes | 139 | $Z'$ mass 4.1 TeV | $\Gamma/m = 1.2\%$ | 2005.05138 |
| | SSM $W' \to \ell\nu$ | 1 $e, \mu$ | – | Yes | 139 | $W'$ mass 6.0 TeV | | 1906.05609 |
| | SSM $W' \to \tau\nu$ | 1 $\tau$ | – | Yes | 36.1 | $W'$ mass 3.7 TeV | | 1801.06992 |
| | HVT $W' \to WZ \to \ell\nu qq$ model B | 1 $e, \mu$ | 2 j / 1 J | Yes | 139 | $W'$ mass 4.3 TeV | $g_V = 3$ | 2004.14636 |
| | HVT $Z' \to ZH$ model B | 0-2 $e, \mu$ | 1-2 b | Yes | 139 | $Z'$ mass 3.2 TeV | $g_V = 3$ | ATLAS-CONF-2020-043 |
| | HVT $W' \to WH$ model B | 0 $e, \mu$ | ≥ 1 b, ≥ 2 J | | 139 | $W'$ mass 3.2 TeV | $g_V = 3$ | 2007.05293 |
| | LRSM $W_R \to tb$ | multi-channel | | | 36.1 | $W_R$ mass 3.25 TeV | | 1807.10473 |
| | LRSM $W_R \to \mu N_R$ | 2 $\mu$ | 1 J | – | 80 | $W_R$ mass 5.0 TeV | $m(N_R) = 0.5$ TeV, $g_L = g_R$ | 1904.12679 |
| CI | CI $qqqq$ | – | 2 j | – | 37.0 | $\Lambda$ 21.8 TeV | $\eta_{LL}^-$ | 1703.09127 |
| | CI $\ell\ell qq$ | 2 $e, \mu$ | – | – | 139 | $\Lambda$ 35.8 TeV | $\eta_{LL}^-$ | 2006.12946 |
| | CI $eebs$ | 2 $e$ | 1 b | – | 139 | $\Lambda$ 1.8 TeV | $g_* = 1$ | ATLAS-CONF-2021-012 |
| | CI $\mu\mu bs$ | 2 $\mu$ | 1 b | – | 139 | $\Lambda$ 2.0 TeV | $g_* = 1$ | ATLAS-CONF-2021-012 |
| | CI $tttt$ | ≥1 $e,\mu$ | ≥1 b, ≥1 j | Yes | 36.1 | $\Lambda$ 2.57 TeV | $\lvert C_{4t}\rvert = 4\pi$ | 1811.02305 |
| DM | Axial-vector med. (Dirac DM) | 0 $e, \mu, \tau, \gamma$ | 1 – 4 j | Yes | 139 | $m_{med}$ 2.1 TeV | $g_q$=0.25, $g_\chi$=1, $m(\chi)$=1 GeV | 2102.10874 |
| | Pseudo-scalar med. (Dirac DM) | 0 $e, \mu, \tau, \gamma$ | 1 – 4 j | Yes | 139 | $m_{med}$ 376 GeV | $g_q$=1, $g_\chi$=1, $m(\chi)$=1 GeV | 2102.10874 |
| | Vector med. $Z'$-2HDM (Dirac DM) | 0 $e, \mu$ | 2 b | Yes | 139 | $m_{med}$ 3.1 TeV | tan$\beta$=1, $g_Z$=0.8, $m(\chi)$=100 GeV | ATLAS-CONF-2021-006 |
| | Pseudo-scalar med. 2HDM+a | 0 $e, \mu$ | 2 b | Yes | 139 | $m_{med}$ 520 GeV | tan$\beta$=1, $g_\chi$=1, $m(\chi)$=10 GeV | ATLAS-CONF-2021-006 |
| | Scalar reson. $\phi \to t\chi$ (Dirac DM) | 0-1 $e, \mu$ | 1 b, 0-1 J | Yes | 36.1 | $m_\phi$ 3.4 TeV | $y$=0.4, $\lambda$=0.2, $m(\chi)$=10 GeV | 1812.09743 |
| LQ | Scalar LQ 1st gen | 2 $e$ | ≥ 2 j | Yes | 139 | LQ mass 1.8 TeV | $\beta = 1$ | 2006.05872 |
| | Scalar LQ 2nd gen | 2 $\mu$ | ≥ 2 j | Yes | 139 | LQ mass 1.7 TeV | $\beta = 1$ | 2006.05872 |
| | Scalar LQ 3rd gen | 1 $\tau$ | 2 b | Yes | 139 | $\mathrm{LQ}_3^u$ mass 1.2 TeV | $\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$ | ATLAS-CONF-2021-008 |
| | Scalar LQ 3rd gen | 0 $e, \mu$ | ≥ 2 j, ≥ 2 b | Yes | 139 | $\mathrm{LQ}_3^u$ mass 1.24 TeV | $\mathcal{B}(\mathrm{LQ}_3^u \to t\nu) = 1$ | 2004.14060 |
| | Scalar LQ 3rd gen | ≥ 2$e, \mu$, ≥ 1$\tau$ | ≥ 1 j, ≥ 1 b | – | 139 | $\mathrm{LQ}_3^d$ mass 1.43 TeV | $\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 1$ | 2101.11582 |
| | Scalar LQ 3rd gen | 0 $e, \mu$, ≥ 1$\tau$ | 0 – 2 j, 2 b | Yes | 139 | $\mathrm{LQ}_3^d$ mass 1.26 TeV | $\mathcal{B}(\mathrm{LQ}_3^d \to b\nu) = 1$ | 2101.12527 |
| Heavy quarks | VLQ $TT \to Ht/Zt/Wb + X$ | multi-channel | | | 36.1 | T mass 1.37 TeV | SU(2) doublet | 1808.02343 |
| | VLQ $BB \to Wt/Zb + X$ | multi-channel | | | 36.1 | B mass 1.34 TeV | SU(2) doublet | 1808.02343 |
| | VLQ $T_{5/3}T_{5/3}\vert T_{5/3} \to Wt + X$ | 2(SS)/≥3 $e,\mu$ | ≥1 b, ≥1 j | Yes | 36.1 | $T_{5/3}$ mass 1.64 TeV | $\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1 | 1807.11883 |
| | VLQ $Y \to Wb + X$ | 1 $e, \mu$ | ≥ 1 b, ≥ 1j | Yes | 36.1 | Y mass 1.85 TeV | $\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1 | 1812.07343 |
| | VLQ $B \to Hb + X$ | 0 $e,\mu$ | ≥ 2 b, ≥ 1j | Yes | 79.8 | B mass 1.21 TeV | singlet, $\kappa_B$= 0.5 | ATLAS-CONF-2018-024 |
| | VLQ $QQ \to WqWq$ | 1 $e, \mu$ | ≥ 4 j | Yes | 20.3 | Q mass 690 GeV | | 1509.04261 |
| Excited fermions | Excited quark $q^* \to qg$ | – | 2 j | – | 139 | $q^*$ mass 6.7 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1910.08447 |
| | Excited quark $q^* \to q\gamma$ | 1 $\gamma$ | 1 j | – | 36.7 | $q^*$ mass 5.3 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1709.10440 |
| | Excited quark $b^* \to bg$ | – | 1 b, 1 j | – | 36.1 | $b^*$ mass 2.6 TeV | | 1805.09299 |
| | Excited lepton $\ell^*$ | 3 $e, \mu$ | – | – | 20.3 | $\ell^*$ mass 3.0 TeV | $\Lambda = 3.0$ TeV | 1411.2921 |
| | Excited lepton $\nu^*$ | 3 $e, \mu, \tau$ | – | – | 20.3 | $\nu^*$ mass 1.6 TeV | $\Lambda = 1.6$ TeV | 1411.2921 |
| Other | Type III Seesaw | 1 $e, \mu$ | ≥ 2 j | Yes | 139 | $N^0$ mass 790 GeV | | 20008.07949 |
| | LRSM Majorana $\nu$ | 2 $\mu$ | 2 j | – | 36.1 | $N_R$ mass 3.2 TeV | $m(W_R) = 4.1$ TeV, $g_L = g_R$ | 1809.11105 |
| | Higgs triplet $H^{\pm\pm} \to \ell\ell$ | 2,3,4 $e, \mu$ (SS) | – | – | 36.1 | $H^{\pm\pm}$ mass 870 GeV | DY production | 1710.09748 |
| | Higgs triplet $H^{\pm\pm} \to \ell\tau$ | 3 $e, \mu, \tau$ | – | – | 20.3 | $H^{\pm\pm}$ mass 400 GeV | DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$ | 1411.2921 |
| | Multi-charged particles | – | – | – | 36.1 | multi-charged particle mass 1.22 TeV | DY production, $\lvert q\rvert = 5e$ | 1812.03673 |
| | Magnetic monopoles | – | – | – | 34.4 | monopole mass 2.37 TeV | DY production, $\lvert g\rvert = 1g_D$, spin 1/2 | 1905.10130 |

🟩 $\sqrt{s}$ = 8 TeV

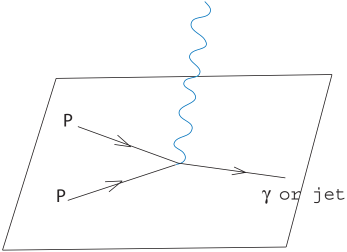
🟨 $\sqrt{s}$ = 13 TeV partial data

🟧 $\sqrt{s}$ = 13 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

# Gravitational radiation in the bulk ⇒ missing energy



Angular distribution ⇒ spin of the graviton

# Black hole production

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

Horowitz-Polchinski '96, Meade-Randall '07

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

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

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

Comparison with Regge excitations : $M_n = M_s\sqrt{n} \Rightarrow$

production of $n \sim 1/g_s^4 \sim 10^4$ string states before reach $M_{\rm BH}$ [55]

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

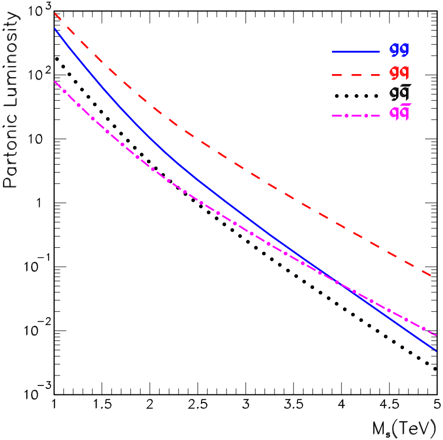
Universal sum over infinite exchange of string (Regge) excitations

Parton luminosities in pp above TeV

are dominated by $gq$, $gg$

$\Rightarrow$ model independent

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



# Cross sections

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

model independent
for any compactification

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

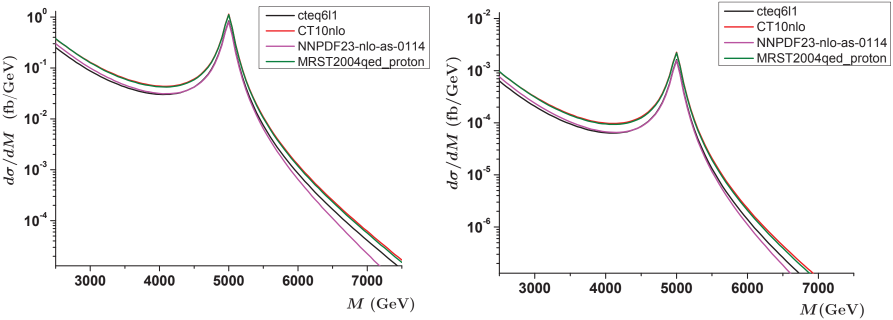
$$\boxed{|\mathcal{M}(gg\to q\bar{q})|^2 = g_{YM}^4\,\frac{t^2+u^2}{s^2}\,\left[\frac{1}{6}\,\frac{1}{tu}\,(tV_t+uV_u)^2-\frac{3}{8}\,V_t\,V_u\right]} \qquad M_s=1$$

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

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

# String Resonances production at Hadron Colliders

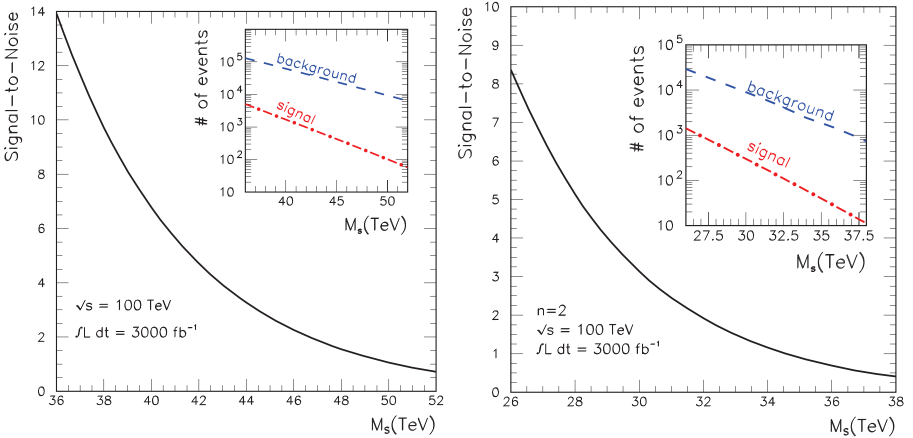
**I.A.-Anchordoqui-Dai-Feng-Goldberg-Huang-Lüst-Stojkovic-Taylor ’14**



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

# String Resonances production at Hadron Colliders

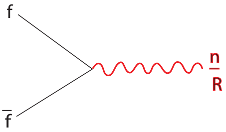
**I.A.-Anchordoqui-Dai-Feng-Goldberg-Huang-Lüst-Stojkovic-Taylor ’14**



[55]

**Localized fermions** (on 3-brane intersections)

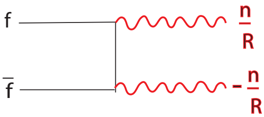
⇒ single production of KK modes I.A.-Benakli '94



- strong bounds indirect effects: $R^{-1} \gtrsim 5\,\mathrm{TeV}$
- new resonances but at most $n = 1$

**Otherwise KK momentum conservation** [65]

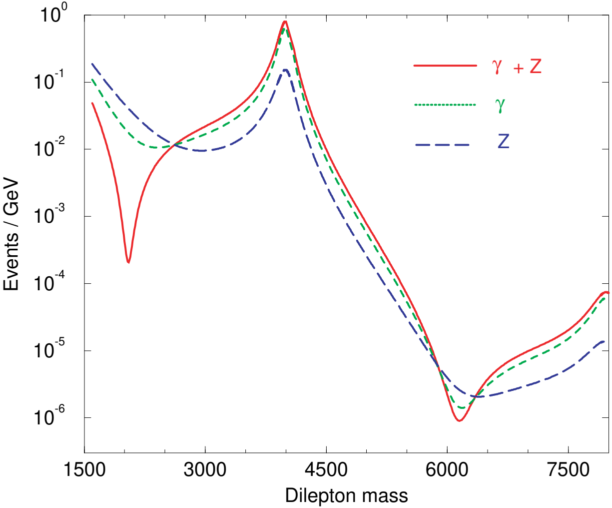
⇒ pair production of KK modes (universal dims)



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

Servant-Tait '02

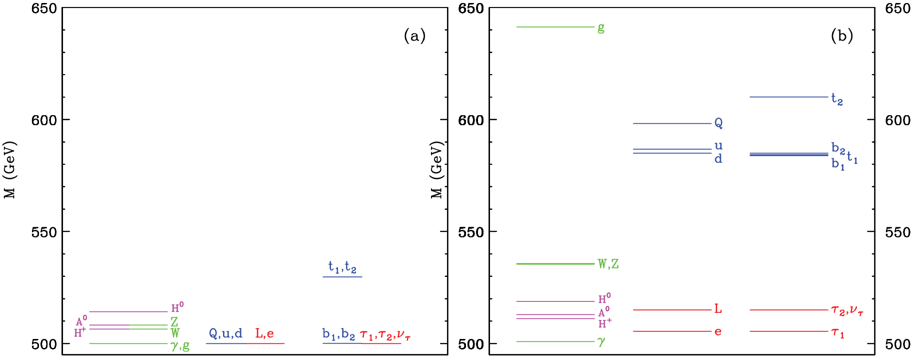
$R^{-1} = 4$ TeV


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

# 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

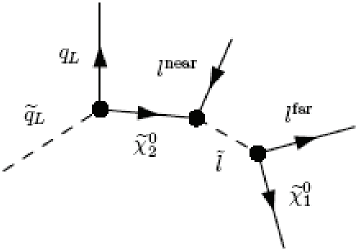
  spin determination important for distinguishing SUSY and UED [55]

| | | | |
|---|---|---|---|
| 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 |

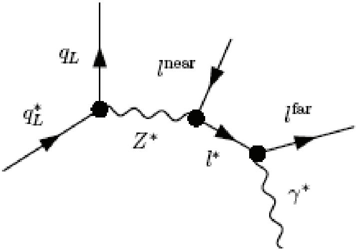
# SUSY vs UED signals at LHC

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

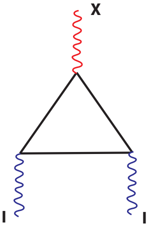
Two kinds of massive $U(1)$'s: I.A.-Kiritsis-Rizos '02

- 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→4d) internal space $\Rightarrow M_{NA} \geq M_A$

or massless in the absence of such anomalies

# Green-Schwarz anomaly cancellation



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

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

cancel the anomaly

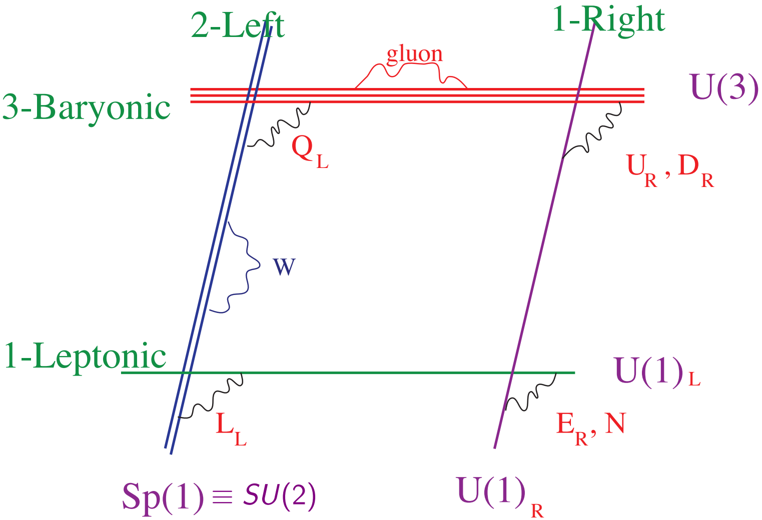
string theory: $\theta =$ Poincaré dual of a 2-form $\quad d\theta = * dB_2$

Heterotic: single universal axion [32]

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

but global symmetry remains in perturbation theory

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



$U(1)^3 \Rightarrow$ hypercharge + B, L [36] [50]

# 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: $\underset{\nwarrow}{\frac{\langle H \rangle^2}{M_s}} LL$

  $\sim$ GeV

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

• Leptophilic $U(1)$s that could explain the $g_\mu - 2$ discrepancy [52]

I.A.-Anchordoqui-Huang-Lüst-Stojkovic-Taylor '21

# 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 → mm range

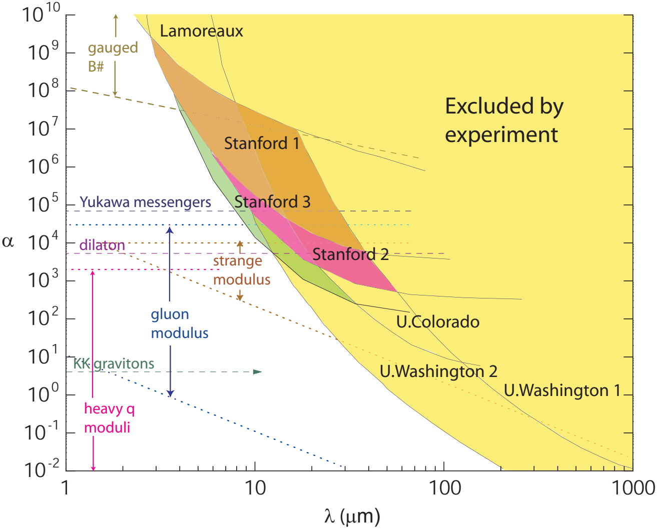
  can be experimentally tested for any number of extra dimensions

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

    $\Rightarrow$ for the same mass much stronger than gravity: $\gtrsim\ 10^6$ [82]

# Experimental limits on short distance forces

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



# More general framework: large number of species

$N$ particle species ⇛ 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 ⇛ $N \sim 10^{32}$ particle species !

2 ways to realize it lowering the string scale

1. Large extra dimensions SM on D-branes [46]

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

2. Effective number of string modes contributing to the BH bound

   $N = \frac{1}{g_s^2}$ with $g_s \simeq 10^{-16}$ SM on NS5-branes in LST

I.A.-Pioline '99, I.A.-Dimopoulos-Giveon '01

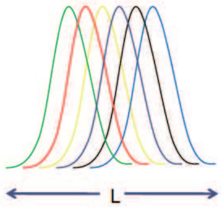
# More general framework: large number of species

$N$ 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 !

# What is LST ? Decouple gravity from NS5-branes

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

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

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

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

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

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

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

at a non-trivial fixed point

parameters: number of branes $N$, string scale $M_s$

# How to study LST ? Using gauge/gravity duality

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

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

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

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

$\rightarrow$ model independent part : $AdS_5$

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

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

Aharony-Berkooz-Kutasov-Seiberg '98

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

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

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

$\rightarrow$ model independent part : linear dilaton

# Put gravity back but weakly coupled

"cut" the space of the extra dimension ⇒ gravity on the brane

Toy 5d bulk model

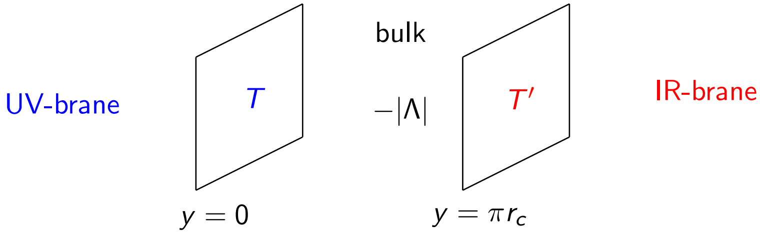
$$S_{bulk} = \int d^4x \int_0^{r_c} dy \sqrt{-g}\, e^{-\Phi} \left(M_5^3 R + M_5^3 (\nabla\Phi)^2 - \Lambda\right)$$

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

Tuning conditions: $T_{vis} = -T_{hid} \leftrightarrow \Lambda < 0$ [80]

# Constant dilaton and AdS metric : Randal Sundrum model

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 $n$

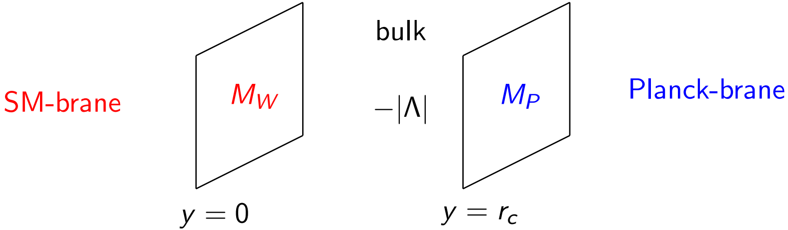
$\Rightarrow$ spin-2 TeV resonances in di-lepton or di-jet channels

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

dilaton $\Phi = -\alpha|y|$ and flat metric $\Rightarrow$

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

$z \sim e^{\alpha y/3} \Rightarrow$ polynomial warp factor + log varying dilaton



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

# LST KK graviton phenomenology

- KK spectrum : $m_n^2 = \left(\frac{n\pi}{r_c}\right)^2 + \frac{\alpha^2}{4}$ ; $n = 1, 2, \ldots$

  $\Rightarrow$ mass gap + dense KK modes $\alpha \sim 1$ TeV $r_c^{-1} \sim 30$ GeV

- couplings : $\frac{1}{\Lambda_n} \sim \frac{1}{(\alpha r_c) M_5}$

  $\Rightarrow$ extra suppression by a factor $(\alpha r_c) \simeq 30$

- width : $1/(\alpha r_c)^2$ suppression $\sim 1$ GeV

  $\Rightarrow$ narrow resonant peaks in di-lepton or di-jet channels

- extrapolates between RS and flat extra dims ($n = 1$)

  $\Rightarrow$ distinct experimental signals

# Conclusions

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