Extra dimensions and string phenomenology in the LHC era

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1. LHC: where do we stand? where do we go?
2. Supersymmetry: is it alive?
3. String phenomenology: what for? main issues
4. High string scale - heterotic string
5. High string scale - type IIA/B and intersecting/magnetized branes
6. Low string scale and large extra dimensions
7. Experimental predictions
8. Warped spaces and holography

Bibliography

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- *An Introduction to perturbative and nonperturbative string theory*
  Ignatios Antoniadis, Guillaume Ovarlez
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- *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

The value of Higgs mass ~ 125 GeV

- consistent with expectation from precision tests of the SM
- favors perturbative physics   quartic coupling $\lambda = m_H^2/v^2 \simeq 1/8$
- 1st elementary scalar in nature signaling perhaps more to come
- triumph of QFT and renormalized perturbation theory!

  Standard Theory has been tested with radiative corrections

Window to new physics ?

- very important to measure precisely its properties and couplings
- several new and old questions wait for answers

  Dark matter, neutrino masses, baryon asymmetry, flavor physics, axions, electroweak scale hierarchy, early cosmology, . . .

Beyond the Standard Theory of Particle Physics: driven by the mass hierarchy problem

Standard picture: low energy supersymmetry

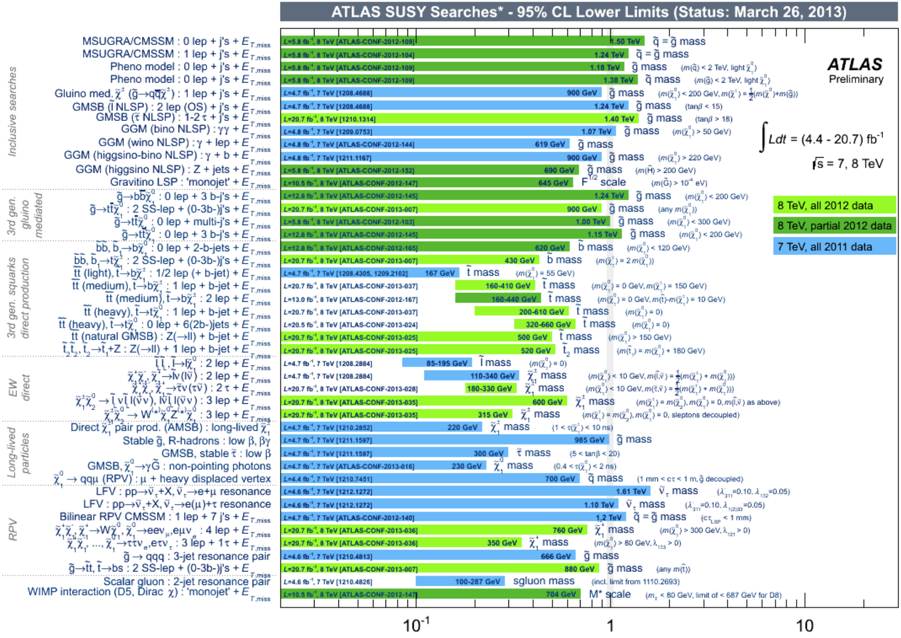
Natural framework: Heterotic string (or high-scale M/F) theory

Advantages:

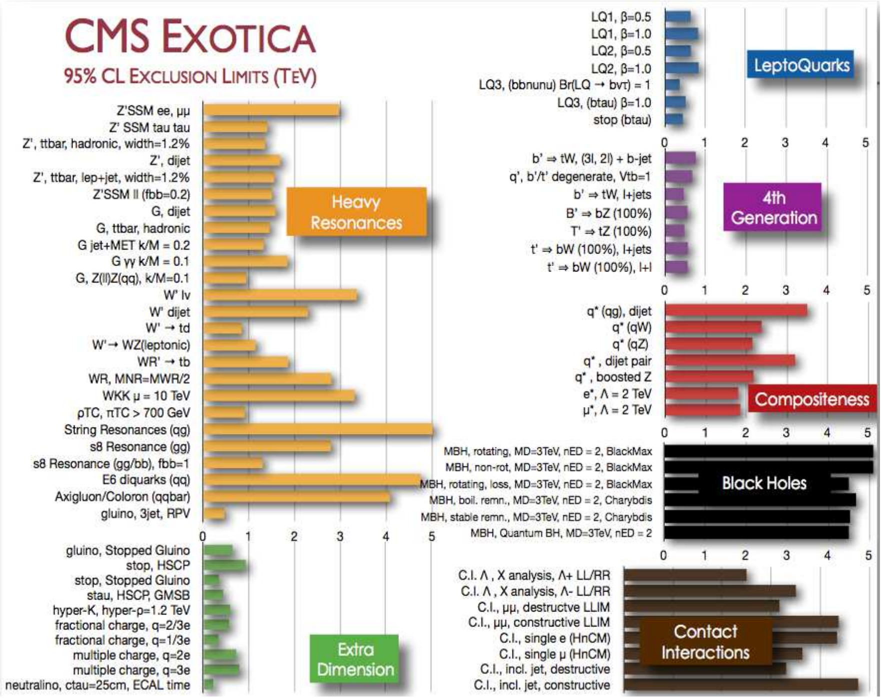
- natural elementary scalars
- gauge coupling unification
- LSP: natural dark matter candidate
- radiative EWSB

Problems:

- too many parameters: soft breaking terms
- MSSM : already a % - ‰ fine-tuning   'little' hierarchy problem



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.


CMS EXOTICA
95% CL EXCLUSION LIMITS (TEV)
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3, (bbnunu) Br(LQ → bντ) = 1
LQ3, (btau) β=1.0
stop (btau)
LeptoQuarks
Z'SSM ee, μμ
Z' SSM tau tau
Z', ttbar, hadronic, width=1.2%
Z', dijet
Z', ttbar, lep+jet, width=1.2%
Z'SSM ll (fbb=0.2)
G, dijet
G, ttbar, hadronic
G jet+MET k/M = 0.2
G γγ k/M = 0.1
G, Z(ll)Z(qq), k/M=0.1
W' lν
W' dijet
W' → td
W'→ WZ(leptonic)
WR' → tb
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
s8 Resonance (gg/bb), fbb=1
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
Heavy Resonances
b' ⇒ tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' ⇒ tW, l+jets
B' ⇒ bZ (100%)
T' ⇒ tZ (100%)
t' ⇒ bW (100%), l+jets
t' ⇒ bW (100%), l+l
4th Generation
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
Compositeness
MBH, rotating, MD=3TeV, nED = 2, BlackMax
MBH, non-rot, MD=3TeV, nED = 2, BlackMax
MBH, rotating, loss, MD=3TeV, nED = 2, BlackMax
MBH, boil. remn., MD=3TeV, nED = 2, Charybdis
MBH, stable remn., MD=3TeV, nED = 2, Charybdis
MBH, Quantum BH, MD=3TeV, nED = 2
Black Holes
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
fractional charge, q=2/3e
fractional charge, q=1/3e
multiple charge, q=2e
multiple charge, q=3e
neutralino, ctau=25cm, ECAL time
Extra Dimension
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive
Contact Interactions
0 1 2 3 4 5

What is next?

What is next?

Physics is an experimental science

- Exploit the full potential of LHC
- Go on and explore the multi TeV energy range

The LHC timeline

LS1 Machine Consolidation

LS2 Machine upgrades for high Luminosity

- Collimation
- Cryogenics
- Injector upgrade for high intensity (lower emittance)
- Phase I for ATLAS : Pixel upgrade, FTK, and new small wheel

LS3 Machine upgrades for high Luminosity

- Upgrade interaction region
- Crab cavities?
- Phase II: full replacement of tracker, new trigger scheme (add L0), readout electronics.

European Strategy Update

Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.

LHC timeline

2009 Start of LHC

Run 1, 7+8 TeV, ~25 fb^{-1} int. lumi

2013/14 Prepare LHC for design *E* & lumi **LS1**

Collect ~30 fb^{-1} per year at 13/14 TeV

2018 Phase-1 upgrade ultimate lumi **LS2**

Twice nominal lumi at 14 TeV, ~100 fb^{-1} per year

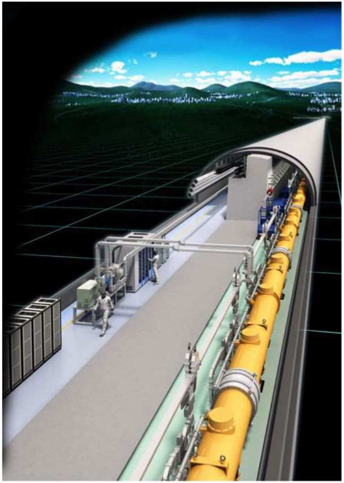
~2022 Phase-2 upgrade to HL-LHC **LS3**

~300 fb^{-1} per year, run up to > 3 ab^{-1} collected

~2030

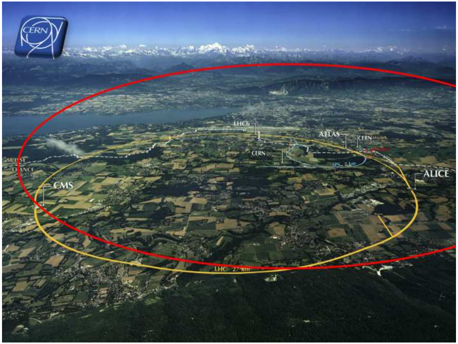
Explore the multi TeV energy range

Linear Colliders - ILC project

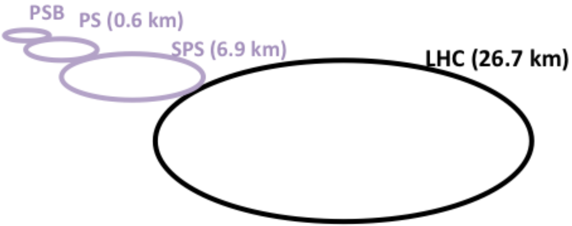


also CLIC at CERN

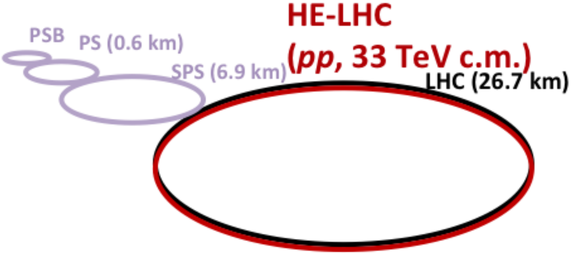
Circular Colliders



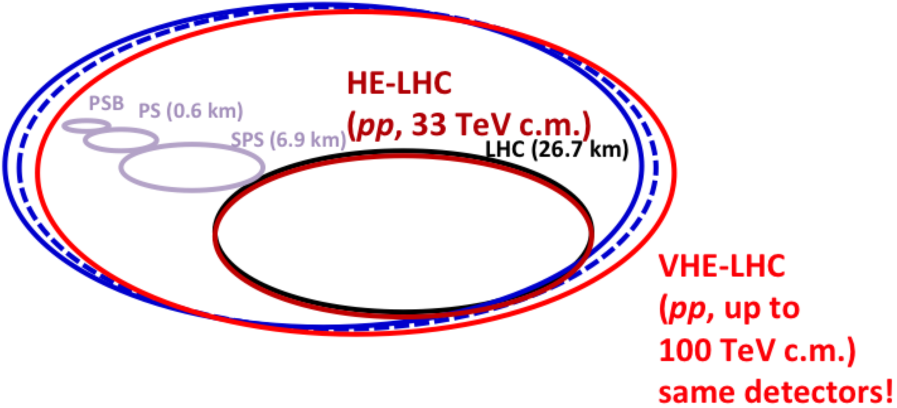
possible long-term strategy



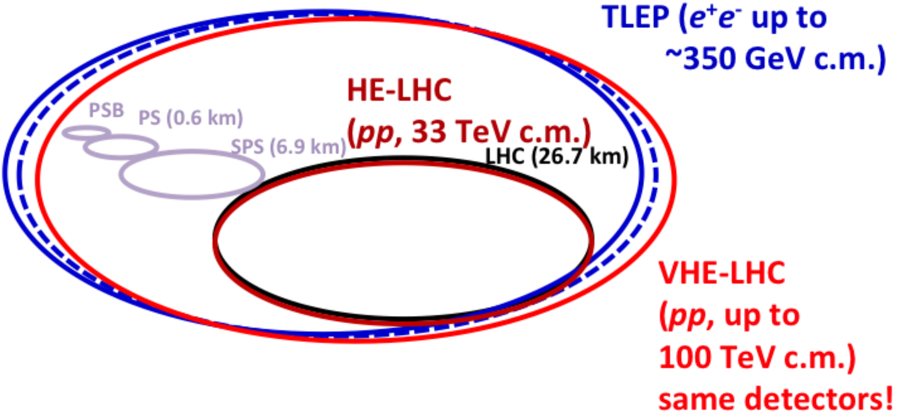
possible long-term strategy



possible long-term strategy



possible long-term strategy



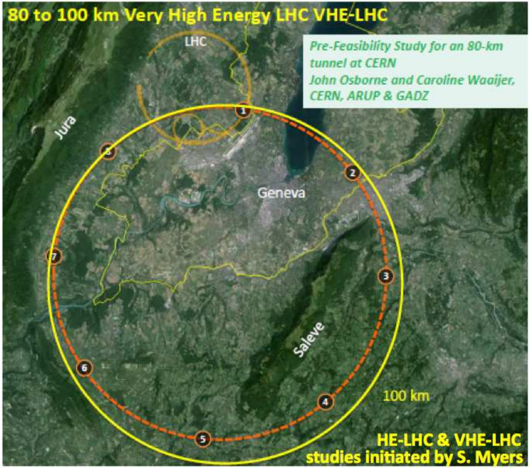
also: $e^{\pm}$ **(120 GeV) – *p* (7 & 50 TeV)** collisions

≥50 years of e^+e^-, *pp*, *ep/A* physics at highest energies

VHE-LHC: location and size

- 100 TeV p-p collider
- CDR and cost review to be ready for next European Strategy Update
- The tunnel could also house a e^+- e^- Higgs factory (TLEP)

	TLEP
circumference	80 km
Beam energy up to	370 GeV c.m.
max no. of IPs	4
Luminosity/IP at 350 GeV c.m.	1.3×10^{34} cm^{-2}s^{-1}
Luminosity/IP at 240 GeV c.m.	4.8×10^{34} cm^{-2}s^{-1}
Luminosity/IP at 160 GeV c.m.	1.6×10^{35} cm^{-2}s^{-1}
Luminosity/IP at 90 GeV c.m.	$5.6\ 10^{35}$ cm^{-2}s^{-1}



A circumference of 100 km is being considered for cost-benefit reasons

20T magnet in 80 km / 16T magnet in 100 km $\rightarrow$ 100 TeV

Future Circular Collider Study - FCC

Mandate

Context

A conceptual design study of options for a future high-energy frontier circular collider at CERN for the post-LHC era shall be carried out, implementing the request in the 2013 update of the European Strategy for Particle Physics (CERN-Council-S/106), which states, inter alia, that:

"..., Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available." and that "CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide."
(http://cds.cern.ch/record/1567258/files/esc-e-106.pdf)

This design study shall be organised on a world-wide international collaboration basis under the auspices of the European Committee for Future Accelerators (ECFA) and shall be available in time for the next update of the European Strategy for Particle Physics, foreseen by 2018.

125 GeV Higgs compatible with supersymmetry

Upper bound on the lightest scalar mass:

$$m_h^2 \lesssim m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde t}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde t}^2}\left(1 - \frac{A_t^2}{12 m_{\tilde t}^2}\right)\right] \lesssim (130\,GeV)^2$$

$m_h \simeq 126$ GeV $\Rightarrow m_{\tilde t} \simeq 3$ TeV or $A_t \simeq 3 m_{\tilde t} \simeq 1.5$ TeV

$\Rightarrow$ % to a few ‰ fine-tuning

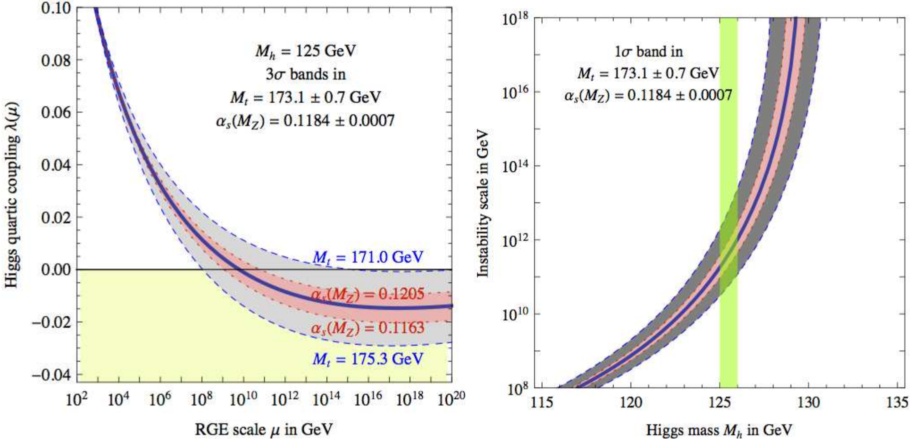
minimum of the potential: $m_Z^2 = 2\dfrac{m_1^1 - m_2^2 \tan_\beta^2}{\tan^2\beta - 1} \sim -2m_2^2 + \cdots$

RG evolution: $m_2^2 = m_2^2(M_{\rm GUT}) - \dfrac{3\lambda_t^2}{4\pi^2} m_{\tilde t}^2 \ln\dfrac{M_{\rm GUT}}{m_{\tilde t}} + \cdots$ [21]

$$\sim m_2^2(M_{\rm GUT}) - \mathcal{O}(1) m_{\tilde t}^2 + \cdots$$

Can the SM be valid at high energies?

Degrassi-Di Vita-Elias Miró-Espinosa-Giudice-Isidori-Strumia '12



Instability of the SM Higgs potential $\Rightarrow$ metastability of the EW vacuum

If the weak scale is tuned ⇒ split supersymmetry is a possibility

Arkani Hamed-Dimopoulos '04, Giudice-Romaninio '04

- natural splitting: gauginos, higgsinos carry R-symmetry, scalars do not
- main good properties of SUSY are maintained

  gauge coupling unification and dark matter candidate
- also no dangerous FCNC, CP violation, ...
- experimentally allowed Higgs mass ⇒ 'mini' split

  $m_S \sim$ few - thousands TeV

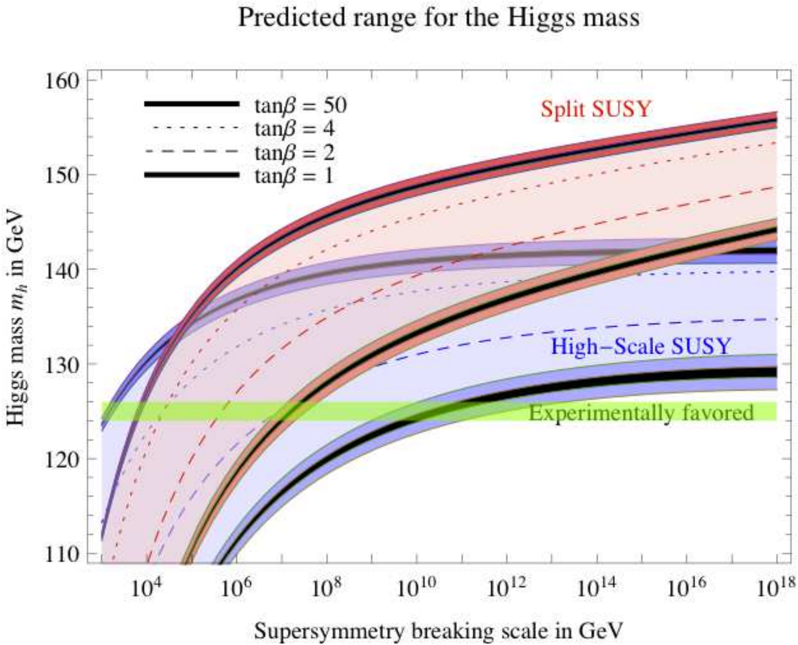
  gauginos: a loop factor lighter than scalars ($\sim m_{3/2}$)
- natural string framework: intersecting (or magnetized) branes

  IA-Dimopoulos '04

  D-brane stacks are supersymmetric with massless gauginos

  intersections have chiral fermions with broken SUSY & massive scalars

Giudice-Strumia '11



Alternative answer: Low UV cutoff $\Lambda \sim$ TeV

- low scale gravity $\Rightarrow$ extra dimensions: large flat or warped

- low string scale $\Rightarrow$ low scale gravity, ultra weak string coupling

$M_s \sim 1$ TeV $\Rightarrow$ volume $R_\perp^n = 10^{32}\, l_s^n$ ($R_\perp \sim .1 - 10^{-13}$ mm for $n = 2 - 6$)

- spectacular model independent predictions

- radical change of high energy physics at the TeV scale

Moreover no little hierarchy problem:

radiative electroweak symmetry breaking with no logs [17]

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

But unification has to be probably dropped

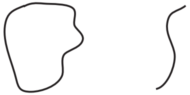
New Dark Matter candidates e.g. in the extra dims

Standard Model of electroweak + strong Interactions :

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

String theory : • Quantum Mechanics + General Relativity

point particle $\rightarrow$ extended objects

• $\rightarrow$  $\Rightarrow$ particles $\equiv$ string vibrations

Framework for unification of all interactions

Mass scale: String tension $M_s \leftrightarrow$ string size: l_s

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 ? [27]

p-plane: extended in p spatial dimensions

$$p = 0\text{: particle,} \quad p = 1\text{: string,}\ldots$$

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

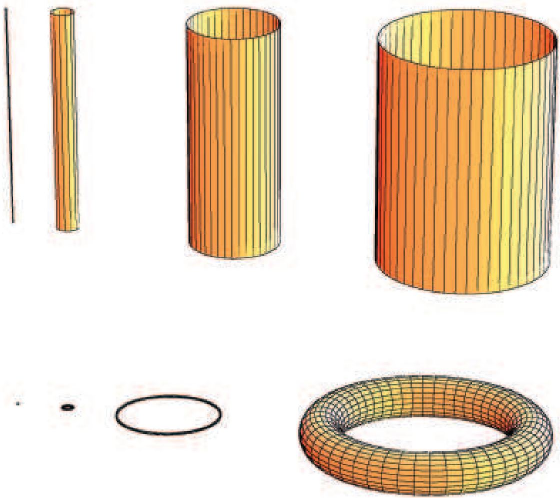
light signal $\Rightarrow$ $E \gtrsim 1$ TeV

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

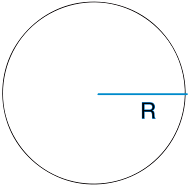
how to detect their existence?

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: $p = \frac{n}{R}$; $n = 0, 1, 2, \ldots$

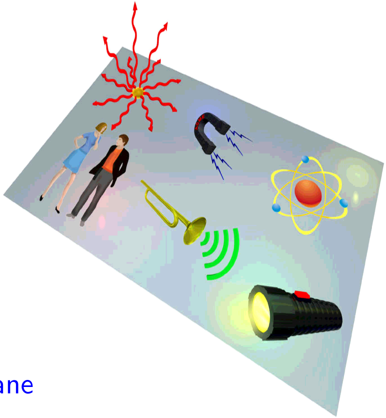
$\Rightarrow$ 3d: tower of Kaluza Klein particles with masses $M_n = n/R$

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

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

$\Leftrightarrow$ propagation in the internal space [23]

Our universe on a membrane

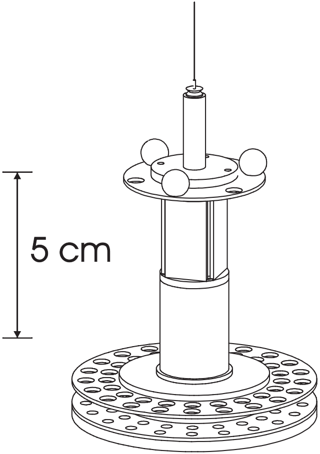


Two types of new dimensions:

- longitudinal: along the membrane
- transverse: "hidden" dimensions

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

Adelberger et al. '06

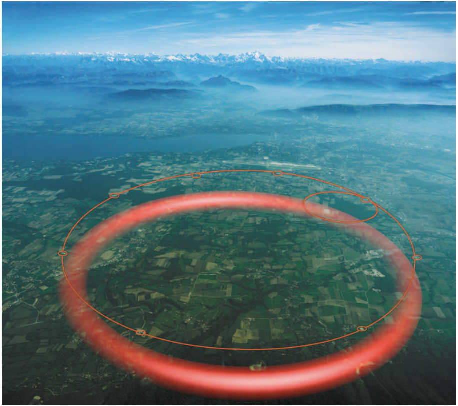


$R_\perp \lesssim 45\ \mu$m at 95% CL

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

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?
- What can we hope to learn from LHC and cosmological observations on string phenomenology?



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 $(M_s^2/M_P \sim \text{TeV})$

  SUSY breaking, strong CP axion, see-saw scale
- Low : TeV $\quad$ (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:

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

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

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 $V_6 \Rightarrow$

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

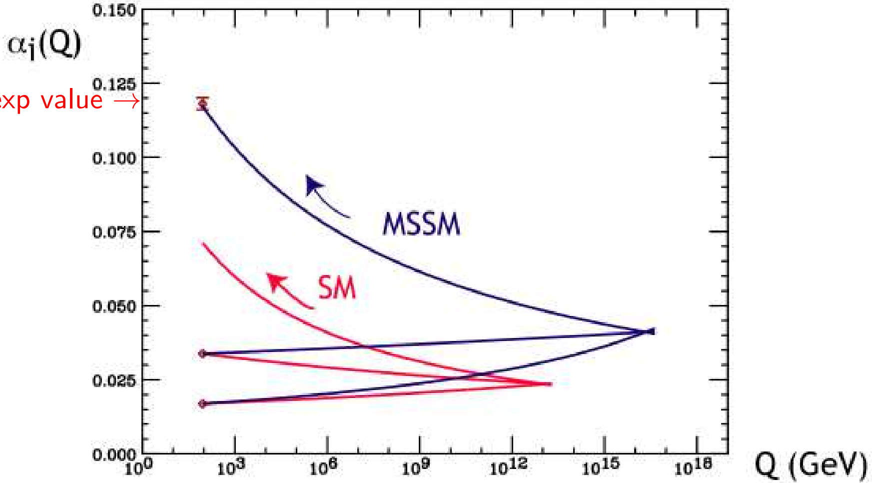
$$M_P^2 = \frac{1}{g^2} M_H^2 \quad \frac{1}{g^2} = \frac{1}{g_H^2} V_6 M_H^6 \quad \Rightarrow \quad M_H = g M_P \quad g_H = g\sqrt{V_6} M_H^3$$

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

GUT prediction of QCD coupling

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

exp value $\rightarrow$



Heterotic string: Spectrum

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

$\left[J_n^a, J_m^b\right] = f^{abc} J_{n+m}^c + k_G\, \delta^{ab} \delta_{n+m}$ $\quad k_G$: 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 $\Rightarrow$ 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

- Higgs from untwisted sector $\Rightarrow$ gauge-Higgs unification

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

- Yukawa couplings: hierarchies à le Froggatt-Nielsen

  discrete symmetries $\Rightarrow$ couplings allowed with powers of a singlet field

  $\lambda_n \sim \Phi^n \qquad \langle\Phi\rangle \sim 0.1\, M_s \rightarrow$ hierarchies

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

  D-term is shifted to $\mathrm{D} + \frac{\mathrm{Tr}\,Q}{192\pi^2} g_H^2$ [65]

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

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

- proton decay: problematic dim-5 operators

  in general need suppression higher than M_s or small couplings

- SU$\!\!\!/$SY in a hidden sector from the other $E_8 \rightarrow$ gravity mediation

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

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

$$\partial_\sigma X^\mu = 0 \text{ at } \sigma = 0 \quad \text{normal derivative vanishes}$$

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

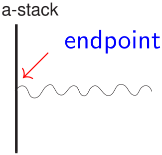
transverse dimensions: $X^{p+1}, \dots, X^9$

$$X^\mu = X_0^\mu \text{ at } \sigma = 0 \quad (\partial_\tau X^\mu = 0 \text{ at } \sigma = 0)$$

Dirichlet conditions: endpoint fixed at the boundary

D-brane spectrum

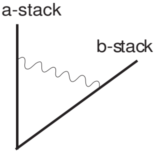
Generic spectrum: N coincident branes $\Rightarrow U(N)$



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 $\Rightarrow$ orientifold planes

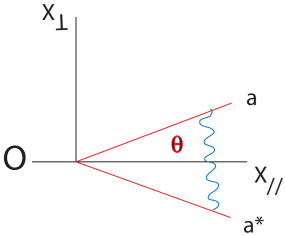
where closed strings change orientation

$\Rightarrow$ mirror branes identified with branes under orientifold action

- strings stretched between two mirror stacks

Orientifold $\rightarrow$

$X_\perp \rightarrow -X_\perp$



$\Rightarrow$ antisymmetric or

symmetric of $U(N_a)$

Minimal Standard Model embedding

General analysis using 3 brane stacks

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

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

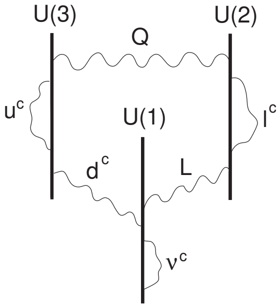
N_i stack of D-branes: $U(N_i) = SU(N_i) \times U(1)_i$

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

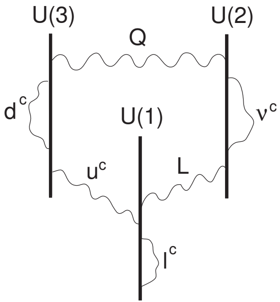
normalization: $\mathrm{Tr}\, T^a T^b = \dfrac{1}{2}\delta^{ab} \Rightarrow \alpha_i = \dfrac{\alpha_{N_i}}{2N_i}$

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

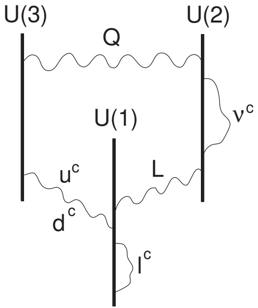
$$\sin^2\theta_W = \frac{g_Y^2}{g_2^2 + g_Y^2} = \frac{1}{g_2^2/g_Y^2 + 1} = \frac{1}{1 + 4c_2^2 + 2c_1^2 g_2^2/g_1^2 + 6c_3^2 g_2^2/g_3^2}$$



Model A

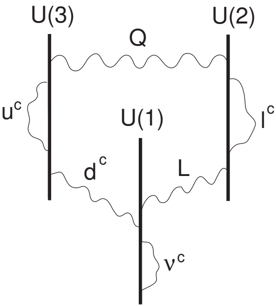


Model B

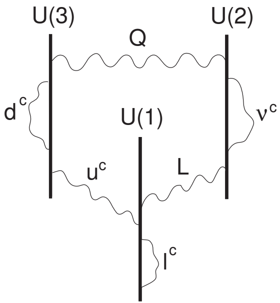


Model C

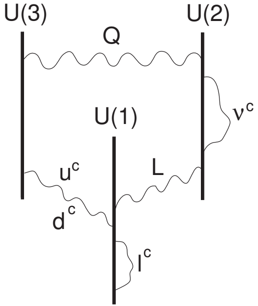
	Model A	Model B	Model C
Q	$(\mathbf{3},\mathbf{2};1,1,0)_{1/6}$	$(\mathbf{3},\mathbf{2};1,\varepsilon_Q,0)_{1/6}$	$(\mathbf{3},\mathbf{2};1,\varepsilon_Q,0)_{1/6}$
u^c	$(\bar{\mathbf{3}},\mathbf{1};2,0,0)_{-2/3}$	$(\bar{\mathbf{3}},\mathbf{1};-1,0,1)_{-2/3}$	$(\bar{\mathbf{3}},\mathbf{1};-1,0,1)_{-2/3}$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



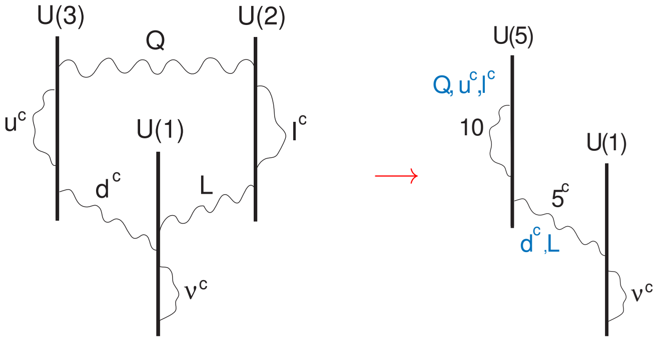
Model B



Model C

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

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


U(3)
U(2)
Q
u^c
U(1)
l^c
d^c
L
ν^c
U(5)
Q, u^c,l^c
10
U(1)
5^c
d^c,L
ν^c

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 [48]

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

$M_p^2 \simeq \frac{1}{g_s^2} M_s^{2+n} R_\perp^n$ $g_s = \alpha$: weak string coupling [31]

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

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

$M_s \sim 1$ TeV $\Rightarrow R_\perp^n = 10^{32}\ l_s^n$ [70]

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

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

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

gravity + gauge kinetic terms

$$\int [d^{10}x]\, \frac{1}{g_s^2} M_s^8\, \mathcal{R}^{(10)} + \int [d^{p+1}x]\, \frac{1}{g_s} M_s^{p-3}\, \mathcal{F}_{MN}^2$$ [32]

Compactification in 4 dims $\Rightarrow$

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

$\Rightarrow$

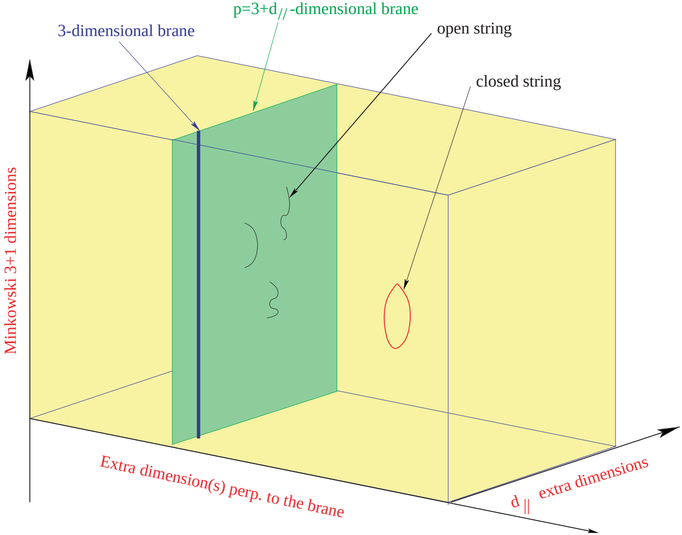
$$g_s = g^2 V_\parallel M_s^{p-3} \lesssim 1 \Rightarrow V_\parallel \sim \text{string size}$$

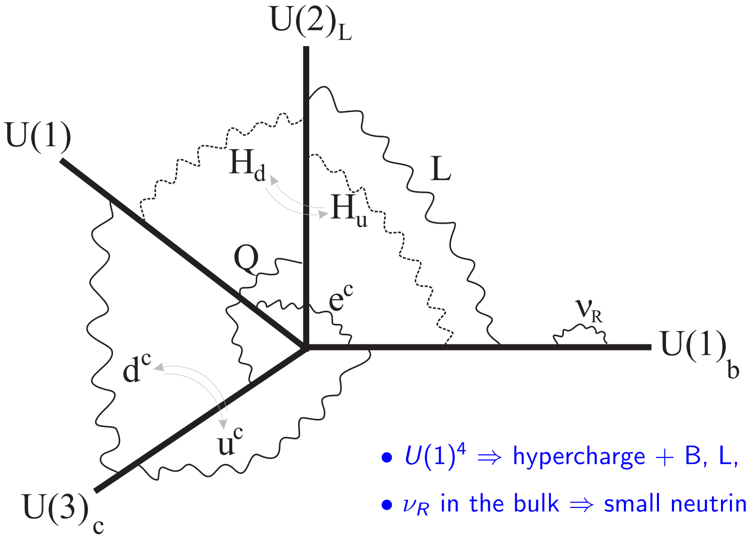
$$\Rightarrow \quad M_P^2 = \frac{V_\perp}{g_s^2} M_s^{2+n} \qquad g_s \simeq g^2$$

Braneworld

2 types of compact extra dimensions:

- parallel ($d_{\parallel}$): $\lesssim 10^{-16}$ cm (TeV) [46]
- 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: $\nu_R(x, y)$ 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: $m_\nu \simeq \frac{g_s v}{R_\perp^{n/2}} \simeq v \frac{M_*}{M_p}$

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

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

Accelerator signatures: 4 different scales

- Gravitational radiation in the bulk $\Rightarrow$ missing energy [53]

  present LHC bounds: $M_* \gtrsim 3-5$ TeV

- Massive string vibrations $\Rightarrow$ e.g. resonances in dijet distribution [55]

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

  higher spin excitations of quarks and gluons with strong interactions

  present LHC limits: $M_s \gtrsim 5$ TeV

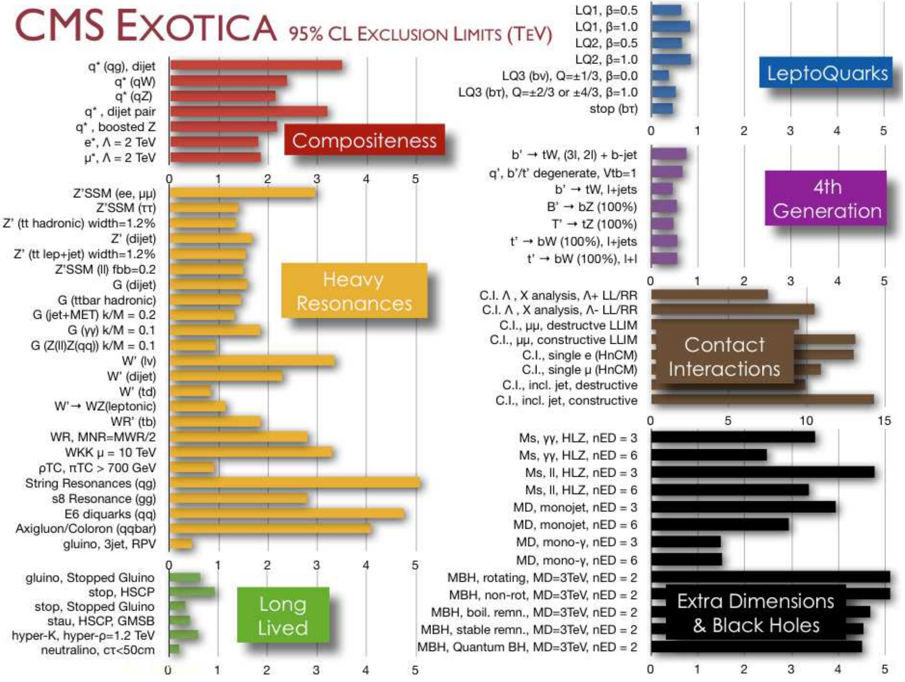
- Large TeV dimensions $\Rightarrow$ KK resonances of SM gauge bosons I.A. '90

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

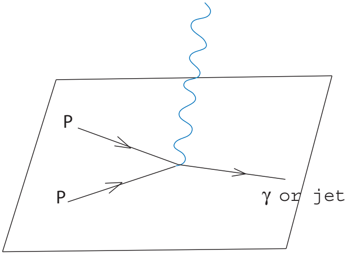
  experimental limits: $R^{-1} \gtrsim 0.5-4$ TeV (UED - localized fermions) [59]

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

  masses suppressed by a loop factor from M_s [64]


CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)
Compositeness
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
Heavy Resonances
Z'SSM (ee, μμ)
Z'SSM (ττ)
Z' (tt hadronic) width=1.2%
Z' (dijet)
Z' (tt lep+jet) width=1.2%
Z'SSM (ll) fbb=0.2
G (dijet)
G (ttbar hadronic)
G (jet+MET) k/M = 0.2
G (γγ) k/M = 0.1
G (Z(ll)Z(qq)) k/M = 0.1
W' (lν)
W' (dijet)
W' (td)
W'→ WZ(leptonic)
WR' (tb)
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
Long Lived
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
neutralino, cτ<50cm
LeptoQuarks
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3 (bν), Q=±1/3, β=0.0
LQ3 (bτ), Q=±2/3 or ±4/3, β=1.0
stop (bτ)
4th Generation
b' → tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' → tW, l+jets
B' → bZ (100%)
T' → tZ (100%)
t' → bW (100%), l+jets
t' → bW (100%), l+l
Contact Interactions
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive
Extra Dimensions & Black Holes
Ms, γγ, HLZ, nED = 3
Ms, γγ, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-γ, nED = 3
MD, mono-γ, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, non-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2

Gravitational radiation in the bulk ⇒ missing energy



Angular distribution ⇒ spin of the graviton

present LHC bounds:

$M_* \gtrsim 3 - 5$ TeV

Collider bounds on $R_\perp$ in mm			
	$n = 2$	$n = 4$	$n = 6$
LEP 2	4.8×10^{-1}	1.9×10^{-8}	6.8×10^{-11}
Tevatron	5.5×10^{-1}	1.4×10^{-8}	4.1×10^{-11}
LHC	4.5×10^{-3}	5.6×10^{-10}	2.7×10^{-12}

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 $M_{\rm BH}$ [51]

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

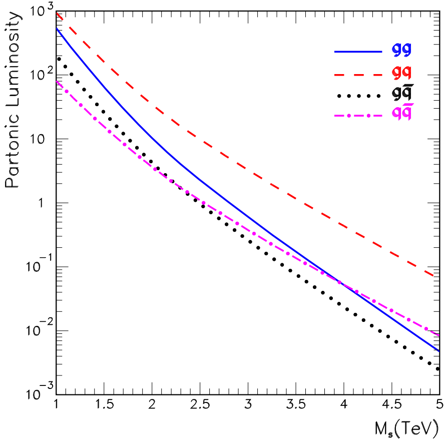
Universal sum over infinite exchange of string (Regge) excitations

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

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

model independent
for any compactification

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

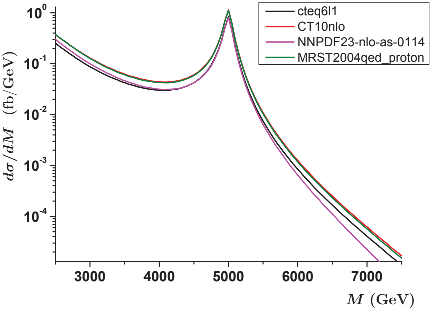
$$|\mathcal{M}(gg\to q\bar q)|^2 = g_{YM}^4\,\frac{t^2+u^2}{s^2}\left[\frac{1}{6}\,\frac{1}{tu}\,(tV_t+uV_u)^2-\frac{3}{8}\,V_t\,V_u\right] \qquad M_s=1$$

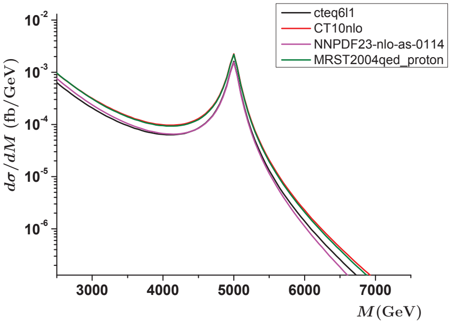
$$V_s=-\frac{tu}{s}\,B(t,u)=1-\frac{2}{3}\pi^2\,tu+\ldots \qquad V_t: s\leftrightarrow t \qquad V_u: s\leftrightarrow u$$

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

String Resonances production at Hadron Colliders

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

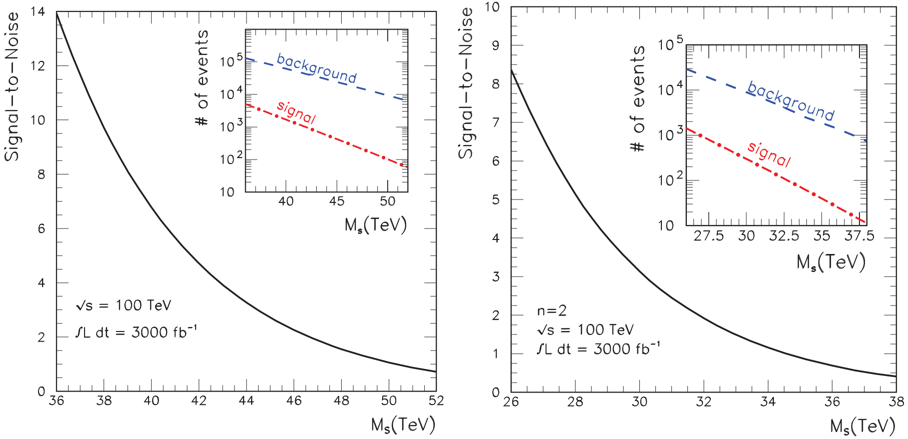




$M_s = 5$ TeV: dijet at LHC14 $\gamma+$ jet

String Resonances production at Hadron Colliders

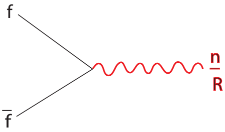
I.A.-Anchordoqui-Dai-Feng-Goldberg-Huang-Lüst-Stojkovic-Taylor ’14



[51]

Localized fermions (on 3-brane intersections)

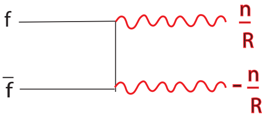
⇒ single production of KK modes   I.A.-Benakli '94



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

Otherwise KK momentum conservation [61]

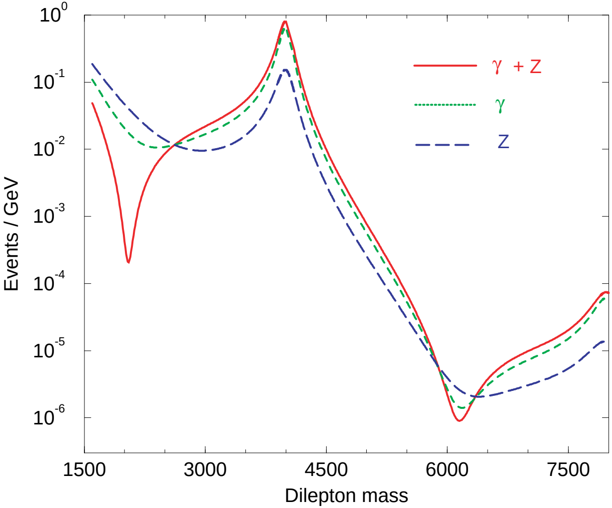
⇒ pair production of KK modes (universal dims)



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

Servant-Tait '02

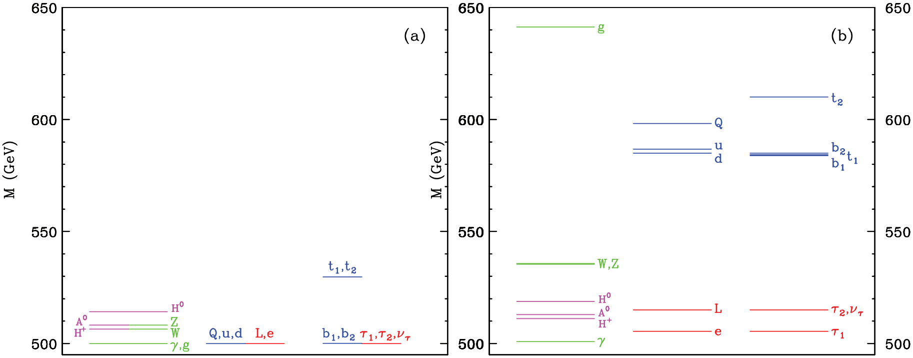
$R^{-1} = 4$ TeV



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

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

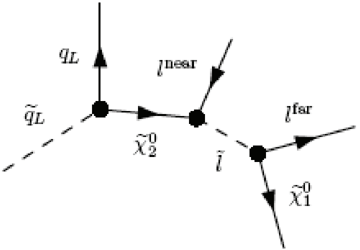
  spin determination important for distinguishing SUSY and UED [51]

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

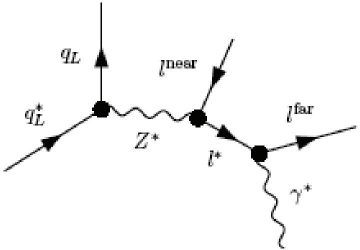
SUSY vs UED signals at LHC

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

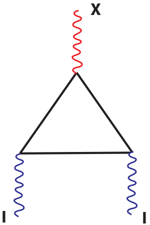
- 4d anomalous $U(1)$'s: $M_A \simeq g_A M_s$

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

$M_{NA} \simeq g_A M_s V_2 \leftarrow$ (6d$\to$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

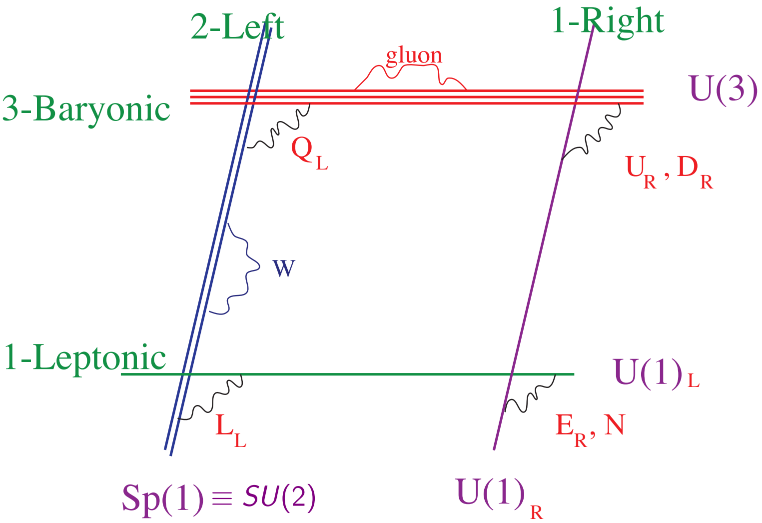
string theory: θ = Poincaré dual of a 2-form $\quad d\theta = * dB_2$

Heterotic: single universal axion [36]

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

- 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

  with possible leptophobic couplings leading to CDF-type Wjj events

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

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

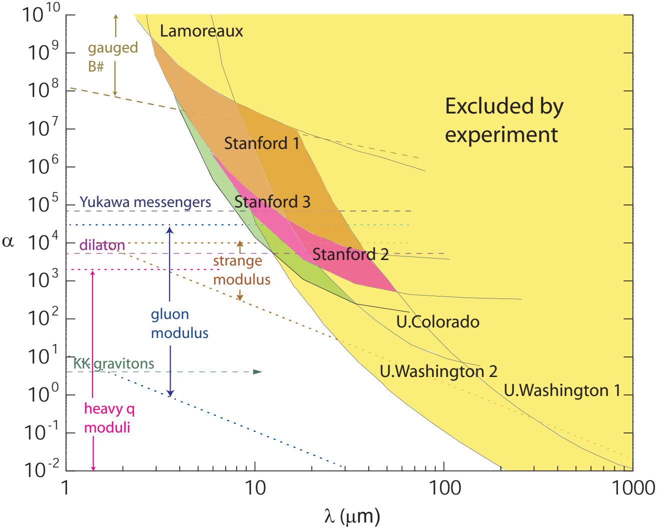
  can be experimentally tested for any number of extra dimensions

  - 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

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



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 !

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

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

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

More general framework: large number of species

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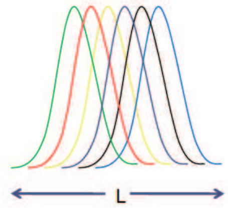
derivation from: black hole evaporation or quantum information storage

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 !

Gauge/Gravity duality $\Rightarrow$ toy 5d bulk model

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

Analogy from D3-branes : AdS_5

NS-5 branes : $(\mathcal{M}_6 \otimes \mathbb{R}_+)$

$\uparrow$ linear dilaton background in 5d flat string-frame metric $\Phi = -\alpha|y|$

Aharony-Berkooz-Kutasov-Seiberg '98

"cut" the space of the extra dimension $\Rightarrow$ gravity on the brane

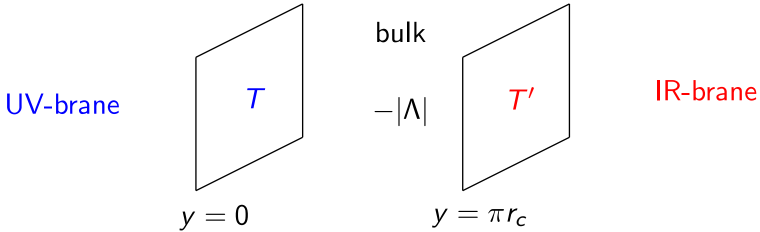
$$S_{bulk} = \int d^4x \int_0^{r_c} dy \sqrt{-g}\, e^{-\Phi} \left(M_5^3 R + M_5^3 (\nabla\Phi)^2 - \Lambda\right)$$

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

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

Constant dilaton and AdS metric : Randal Sundrum model

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



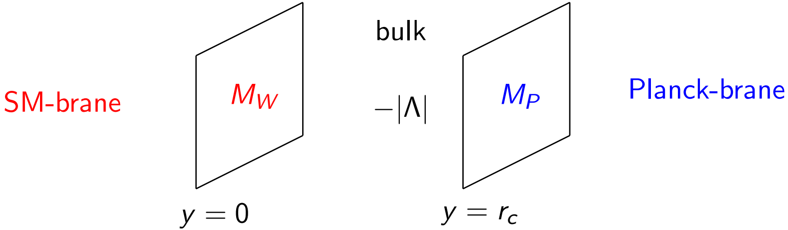
- exponential hierarchy: $M_W = M_P e^{-2kr_c}$ $M_P^2 \sim M_5^3/k$ $M_5 \sim M_{GUT}$
- 4d gravity localized on the UV-brane, but KK gravitons on the IR

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

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

- Discovery of a Higgs scalar at the LHC:

  important milestone of the LHC research program
- Precise measurement of its couplings is of primary importance
- Hint on the origin of mass hierarchy and of BSM physics
  - natural or unnatural SUSY?
  - low string scale in some realization?
  - something new and unexpected?

  all options are still open
- LHC enters a new era with possible new discoveries
- Future plans to explore the 10-100 TeV energy frontier