Aspects of string phenomenology

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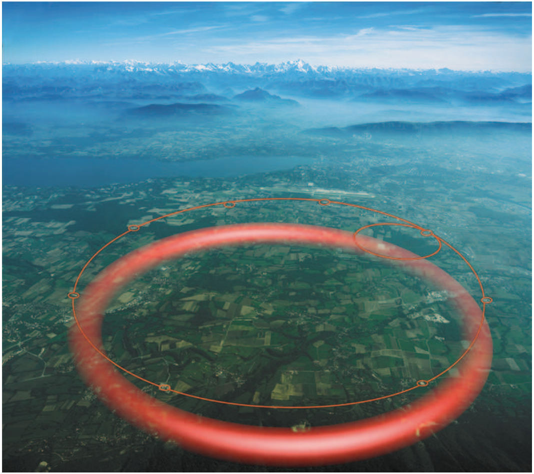
1. main questions, mass hierarchy and list of possibilities
2. general issues of high string scale

   heterotic string and intersecting branes
3. models and phenomenology of low string scale

   large extra dimensions and experimental predictions

Connect string theory to the real world

- Are there low energy string predictions testable at LHC ?
- What can we hope to learn from LHC on string phenomenology ?



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

- arbitrary parameter : Planck mass $M_P \longrightarrow$ TeV
- physical motivations $\Rrightarrow$ favored energy regions:

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

  SUSY breaking, strong CP axion, see-saw scale
- Low : TeV (hierarchy problem)

M-theory, F-theory: see H. Verlinde's lectures

Mass hierarchy problem

Higgs mass: very sensitive to high energy physics $m_H \sim$ UV cutoff Λ

why gravity is so weak compared to the other interactions? $\Lambda = M_P$ [9]

Possible answer (alternative to supersymmetry): Low UV cutoff $\Lambda \sim$ TeV

- low scale gravity $\Rightarrow$ [6]
  large extra dimensions, warped dimensions, DGP localized gravity
- low string scale $\Rightarrow$ low scale gravity, ultra weak string coupling

Experimentally testable framework:

- spectacular model independent predictions
- radical change of high energy physics at the TeV scale
  explicit model building is not necessary at this moment [22]

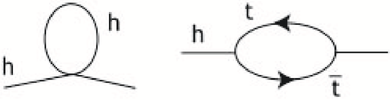
but unification has to be probably dropped

Mass hierarchy problem

Higgs mass: very sensitive to high energy physics

1-loop radiative corrections:

dominant contributions:



$$\mu_{\rm eff}^2 = \mu_{\rm bare}^2 + \left(\frac{\lambda}{8\pi^2} - \frac{3\lambda_t^2}{8\pi^2}\right)\Lambda^2 + \cdots$$

UV cutoff: $\int^\Lambda \frac{d^4k}{k^2}$ scale of new physics

High-energy validity of the Standard Model : $\Lambda >> \mathcal{O}(100)$ GeV $\Rightarrow$

"unatural" fine-tuning between $\mu_{\rm bare}^2$ and radiative corrections

order by order

Mass hierarchy problem

example: $\Lambda \sim \mathcal{O}(M_{\rm Planck}) \sim 10^{19}$ GeV, loop factor $\sim 10^{-2}$

$$\Rightarrow \mu^2_{1-\rm loop} \sim 10^{-2} \times 10^{38} = \pm 10^{36}\ (\text{GeV})^2$$

$$\text{need } \mu^2_{\rm bare} \sim \mp 10^{36}\ (\text{GeV})^2 - 10^4\ (\text{GeV})^2$$

- adjustment at the level of 1 part per 10^{32} $\mu^2_{\rm bare}/\mu^2_{1\ \rm loop} = -1 \mp 10^{-32}$
- new adjustment at the next order, etc

  highest order N: $\left(10^{-2}\right)^N \times 10^{38} \lesssim 10^4 \Rightarrow N \gtrsim 18$ loops !
- no fine tuning : $10^{-2}\Lambda^2 \lesssim 10^4\ (\text{GeV})^2 \Rightarrow \Lambda \lesssim 1$ TeV

  $\rightarrow$ new physics within LHC range ! [8] [4]

Advantages of SUSY

- natural elementary scalars
- gauge coupling unification: theory perturbative up to the GUT scale
- LSP: natural dark matter candidate
- extension of space-time symmetry: new Grassmann dimensions
- prediction of light Higgs
- rich spectrum of new particles within LHC reach

Problems of SUSY

- too many parameters: soft breaking terms

  SUSY breaking mechanism $\Rightarrow$ dynamical aspect of the hierarchy

  $+$ theory of soft terms

- SM global symmetries are not automatic

  B, L from R-parity, conditions on soft terms for FCNC suppression

- SUSY GUTs: no satisfactory model

  doublet/splitting, large Higgs reps, strong coupling above M_{GUT}

- μ problem: SUSY mass parameter but of the order of the soft terms

- SUSY not yet discovered $\Rightarrow$ already a few % fine-tuning [6]

  'little' hierarchy problem [4]

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

$E = m_{\rm proton} \Rightarrow \frac{F_{\rm grav}}{F_{\rm el}} = \frac{G_N m^2_{\rm proton}}{e^2} \simeq 10^{-40} \Rightarrow$ Gravity is very weak !

At what energy gravitation becomes comparable to the other interactions?

$M_{\rm Planck} \simeq 10^{19}$ GeV $\rightarrow$ Planck length: 10^{-33} cm

$10^{15} \times$ the LHC energy! [4]

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:

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

in GUTs only one prediction from 3 gauge couplings unification: $\sin^2\theta_W$ [12]

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

but loose predictivity [13]

Heterotic string

gravity + gauge kinetic terms [24]

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

simplified units: $2 = \pi = 1$

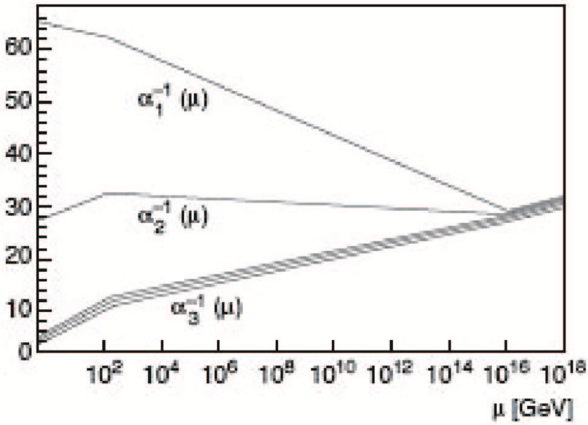
Compactification in 4 dims on a 6-dim manifold of volume $V_6 \Rightarrow$

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

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

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

Gauge coupling unification



[10]

Heterotic string: Spectrum

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

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

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

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

Schellekens '90

- no adjoints to break GUT groups

(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

string constructions based on $Z_6' = Z_3 \times Z_2$ orbifold

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

- GUT breaking to SM by discrete Wilson lines

  on non-contractible cycles

- 2 'large' dimensions $\Rightarrow M_{\rm GUT}$ = compactification scale

  solve GUT scale problem: need universal thresholds above $M_{\rm GUT}$

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

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

- 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_s or small couplings

- SUSY breaking in a hidden sector from the other E_8

  $\rightarrow$ gravity 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

moduli stabilization by fluxes (RR-forms or internal magnetic fields)

however GUTs: problematic:

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

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

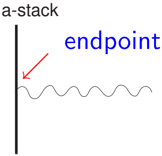
  $\Rightarrow$ cannot balance charges with $SU(5)$ singlets

  can be generated by D-brane instantons but ...
- no Majorana neutrino masses (same reason but instantons can do)

  or alternatively generate exp suppressed Dirac masses [4]

A D-brane embedding of the Standard Model

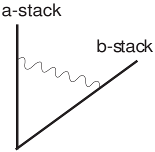
Generic spectrum: N coincident branes $\Rightarrow$ $U(N)$



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

$\Rightarrow$ "baryon" number

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



- oriented strings : need at least 4 brane-stacks

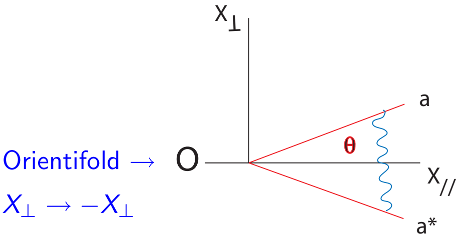
- minimal choice: $U(3) \times U(2) \times U(1)$

color branes (g_3) weak branes (g_2)

Non oriented strings ⇒ orientifold planes

⇒ mirror branes   identified with branes under orientifold action

- strings stretched between two mirror stacks



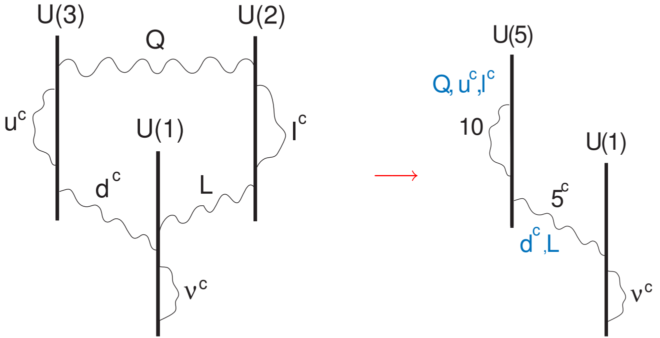
⇒ antisymmetric or symmetric of $U(N_a)$

General analysis using 3 brane stacks : $U(3) \times U(2) \times U(1)$

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

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

⇒ 3 models: antisymmetric is u^c, d^c or none   I.A.-Dimopoulos '04



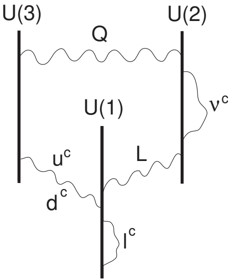
Full string embedding with all geometric moduli stabilized:

- all extra $U(1)$'s broken $\Rightarrow$ 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

$\rightarrow$ gauge mediation

Problem common in all D-brane GUTs: absence of top Yukawa coupling

can be avoided in a $U(3) \times U(2) \times U(1)$ 3-stack model



$\Rightarrow HQu^c, H'Qd^c \neq 0$ all Yukawa's exist

but unification is not guaranteed

although not excluded [4]

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

- gravity: closed strings
- gauge interactions: open strings

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

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

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

$M_P^2 \simeq \frac{1}{\alpha^2} M_s^{2+n} R_{\perp}^n$ $\alpha = g_s$ [24]

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

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

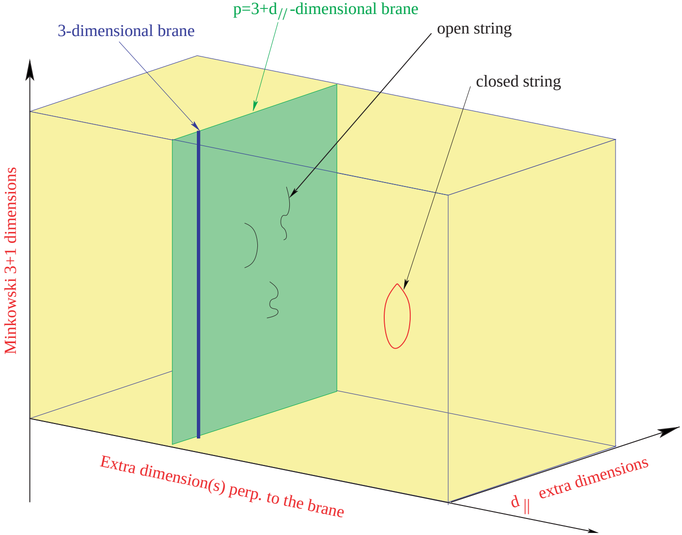
$M_s \sim 1$ TeV $\Rightarrow R_{\perp} \sim .1 - 10^{-13}$ mm $(n = 2-6)$ [25] [??]

weak string coupling: $g_s = \alpha$ [27]

Braneworld

2 types of compact extra dimensions:

- parallel ($d_{\parallel}$): $\lesssim 10^{-16}$ cm (TeV) [52]
- transverse ($\perp$): $\lesssim 0.1$ mm (meV)



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

gravity + gauge kinetic terms

$$\int [d^{10}x]\, \frac{1}{g_s^2} M_s^8\, \mathcal{R}^{(10)} + \int [d^{p+1}x]\, \frac{1}{g_s} M_s^6\, \mathcal{F}^2_{MN}$$ [11]

Compactification in 4 dims $\Rightarrow$

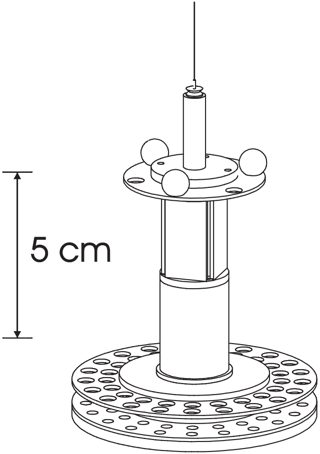
$$\int [d^4x]\, \underbrace{\frac{V_6}{g_s^2} M_s^8}_{= M_P^2}\, \mathcal{R}^{(4)} + \int [d^4x]\, \underbrace{\frac{V_\parallel}{g_s} M_s^{p-3}}_{= 1/g^2}\, \mathcal{F}^2_{\mu\nu} \qquad V_6 = V_\parallel V_\perp$$

$\Rightarrow$

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

$$\Rightarrow \quad M_P^2 = \frac{V_\perp}{g_s^2} M_s^{2+n} \qquad g_s \simeq g^2$$ [22] [29]

Adelberger et al. '06



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

- dark-energy length scale $\approx 85\mu$m [22] [47]

Experiment: 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

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

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

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

$\Rightarrow$ Gravity modification at large (cosmological) and short distances ?

string realization of large extra dimensions

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

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

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

Requirements:

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

  volume by α'-corrections $\rightarrow$ exponentially large

Experimental predictions

- particle accelerators

  - Large TeV dimensions   seen by SM gauge interactions

    $\Rightarrow$ KK resonances of SM gauge bosons   I.A. '90

  - Extra large submm dimensions   transverse

    $\Rightarrow$ missing energy from gravity radiation in the bulk [39] [??]

  - string physics and possible strong gravity effects [41]

- microgravity experiments [47]

  - gravity modifications at short distances

  - new submillimeter forces

Large TeV dimensions

longitudinal dimensions: $R^{-1} \lesssim M_s \Rightarrow R^{-1}$ first scale of new physics

increasing the energy

- could happen for some of the internal dims
- explain coupling constant ratios g_2/g_3 [24]
- susy breaking
- fermion masses displace light generations

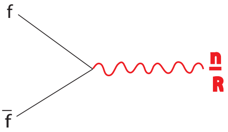
Massive tower of Kaluza Klein modes for Standard Model particles

$$M_n^2 = M_0^2 + \frac{n^2}{R^2} \quad ; \quad n = \pm 1, \pm 2, \dots$$

$\Rightarrow$ excited states of photon, $W^{\pm}$, Z, gluons

Localized fermions (on 3-brane intersections) [52]

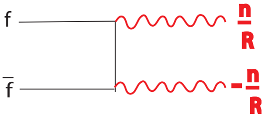
⇒ single production of KK modes I.A.-Benakli '94



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

Otherwise KK momentum conservation [33] [28]

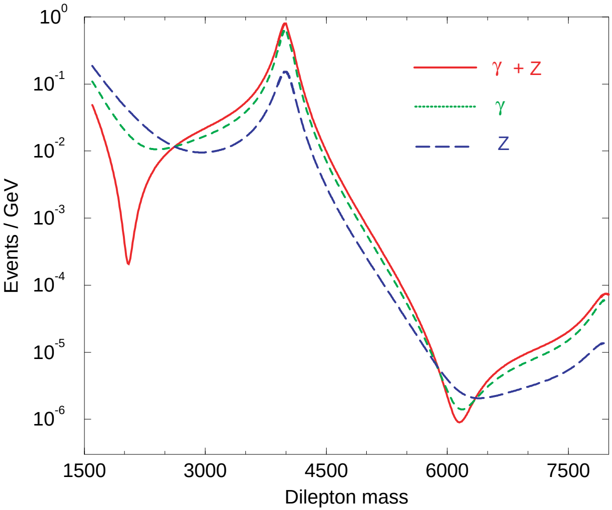
⇒ pair production of KK modes (universal dims)



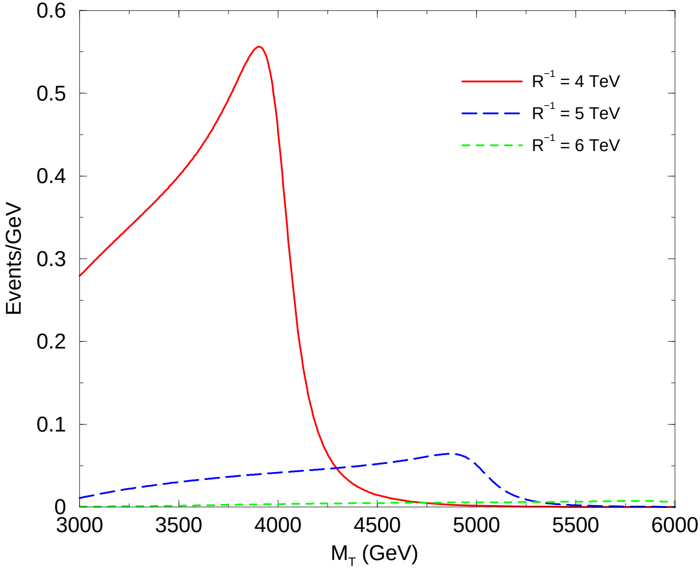
- weak bounds $R^{-1} \gtrsim$ 300-500 GeV
- no resonances
- lightest KK stable : dark matter candidate

Servant-Tait '02

$R^{-1} = 4$ TeV I.A.-Benakli-Quiros '94, '99



KK W-production at LHC in the $l\nu$ channel [30]



Universal extra dimensions

- All Standard Model fields propagate in the extra dimension(s)
- Translation invariance $\Rightarrow$ momentum conservation

  e.g. $\langle \phi_n \phi_m \phi_l \rangle \propto \delta_{n+m+l,0}$ ϕ_n : n-th KK excitation of ϕ

- No tree-level contribution to SM processes involving only 0-modes
- However chirality $\Rightarrow$ orbifolding e.g. S^1 (circle) $\rightarrow S^1/\mathbb{Z}_2$ (interval)

  $\Rightarrow$ translation invariance is broken

- But KK-parity remains : KK-number even/odd $\rightarrow$ KK-parity +/-1

  $\Rightarrow$ lightest KK-odd particle is stable

- All SM gauge bosons have internal components $A_M, M = 0 \dots D-1$

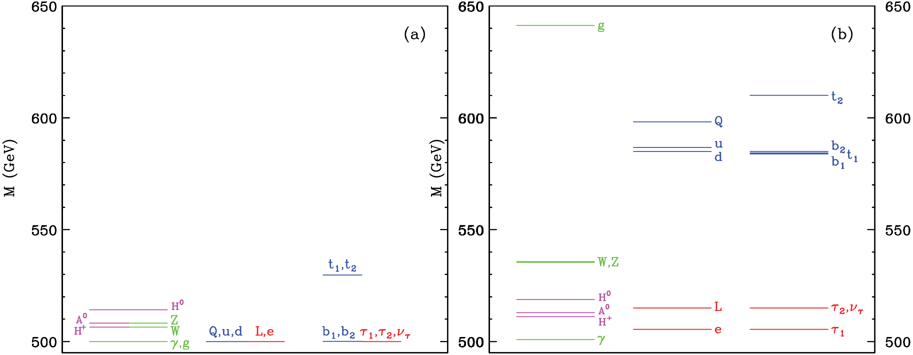
  - one gets eaten to give mass to 4d KK-vectors
  - the remaining $D-5$ form adjoint scalars (no extra scalar in $D=5$)

Mass spectrum

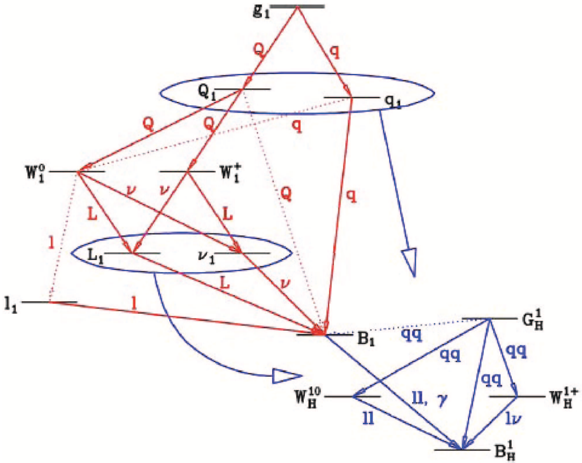
Radiative corrections ⇛ mass shifts that lift degeneracy at lowest KK level

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

Cheng-Matchev-Schmaltz '02



1st KK of hypercharge boson B_1^μ in $D = 5$ or adjoint scalar B_H^1 in $D = 6$



UED hadron collider phenomenology

- large rates for KK-quark and KK-gluon production

  LHC: 1-100 pb for $R^{-1} \lesssim 800$ GeV

- cascade decays via KK-W bosons and KK-leptons

  determine particle properties from different distributions

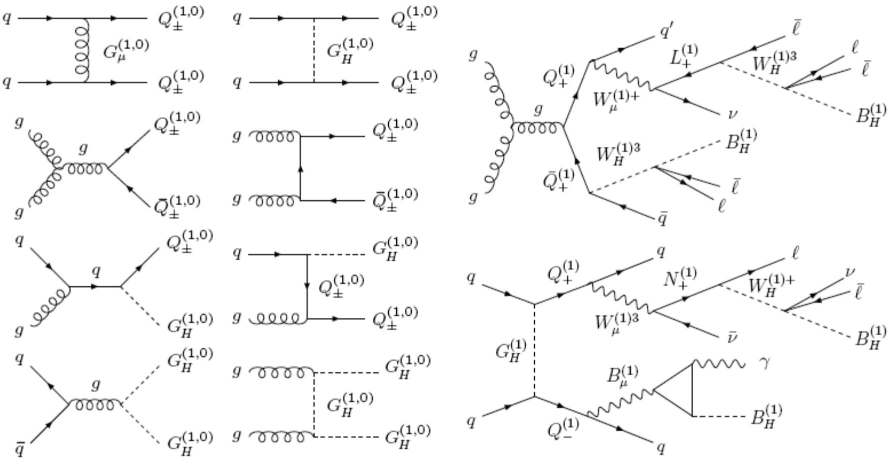
- missing energy from LKP: weakly interacting escaping detection

- phenomenology similar to supersymmetry [38]

  spin determination important for distinguishing SUSY and UED [30] [28]

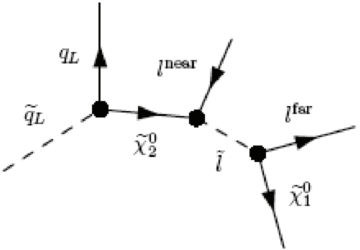
gluino	1/2	KK-gluon	1
squark	0	KK-quark	1/2
chargino	1/2	KK-W boson	1
slepton	0	KK-lepton	1/2
neutralino	1/2	KK-Z boson	1

Production at LHC

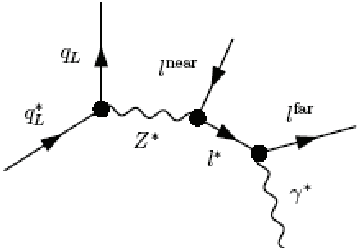


Example: jet dilepton final state [36]

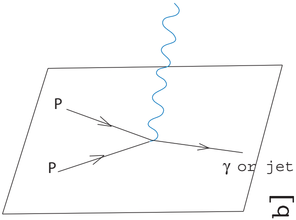
SUSY

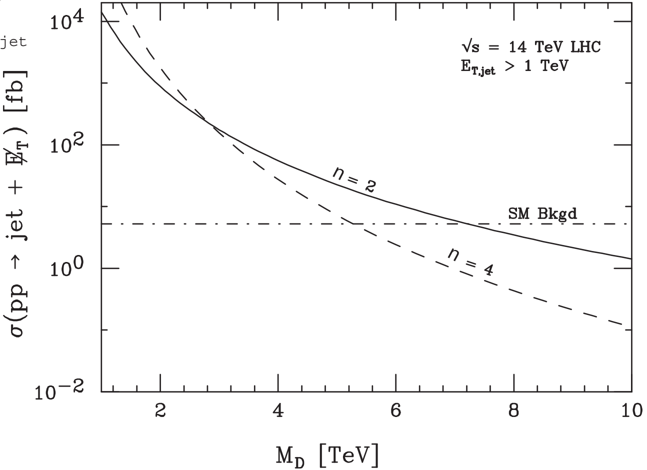


UED



Giudice-Rattazzi-Wells '98





Angular distribution ⇒ spin of the graviton [28]

Limits on $R_\perp$ in mm

Experiment	$R_\perp(n=2)$	$R_\perp(n=4)$	$R_\perp(n=6)$
Collider bounds			
LEP 2	4.8×10^{-1}	1.9×10^{-8}	6.8×10^{-11}
Tevatron	5.5×10^{-1}	1.4×10^{-8}	4.1×10^{-11}
LHC	4.5×10^{-3}	5.6×10^{-10}	2.7×10^{-12}
NLC	1.2×10^{-2}	1.2×10^{-9}	6.5×10^{-12}
Astrophysics/cosmology bounds			
SN1987A	3×10^{-4}	1×10^{-8}	6×10^{-10}
COMPTEL	5×10^{-5}	-	-

Massive string vibrations

indirect effects: virtual exchanges $\Rightarrow$ effective interactions

e.g. four-fermion operators

Actual limits: Matter fermions on

- same set of branes $\Rightarrow M_s \gtrsim 500$ GeV dim-8: $\frac{g^2}{M_s^4}(\bar{\psi}\partial\psi)^2$
- brane intersections :$M_s \gtrsim 2-3$ TeV dim-6: $\frac{g^2}{M_s^2}(\bar{\psi}\psi)^2$

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

High energies $\Rightarrow$

- direct production: string physics
- strong gravity: production of micro-black holes? [46]

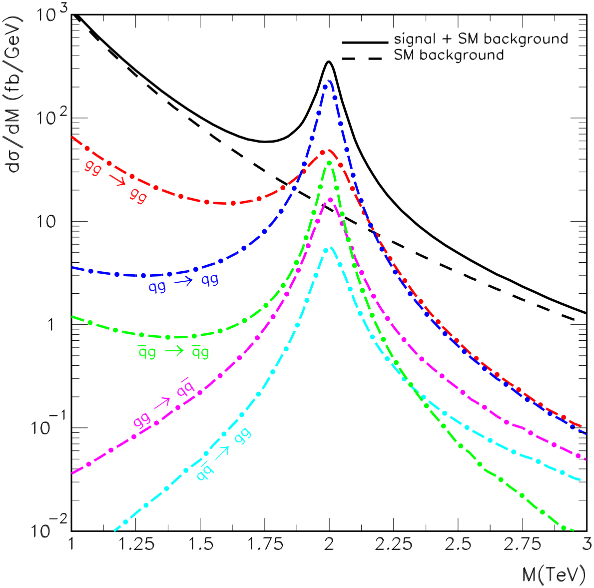
Giddings-Thomas, Dimopoulos-Landsberg '01

Universal deviation from Standard Model in jet distribution

$M_s = 2$ TeV

Width $=$ 15-150 GeV

Anchordoqui-Goldberg-Lüst-Nawata-Taylor-Stieberger '08 [41]



Tree N-point superstring amplitudes in 4 dims

involving at most 2 fermions and gluons:

completely model independent for any string compactification

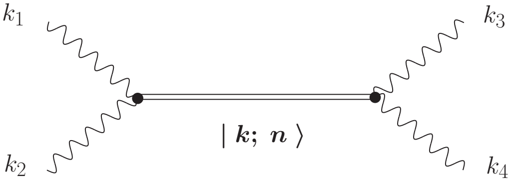
any number of supersymmetries, even none

No intermediate exchange of KK, windings or graviton emmission

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

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

maximal spin: $n + 1$



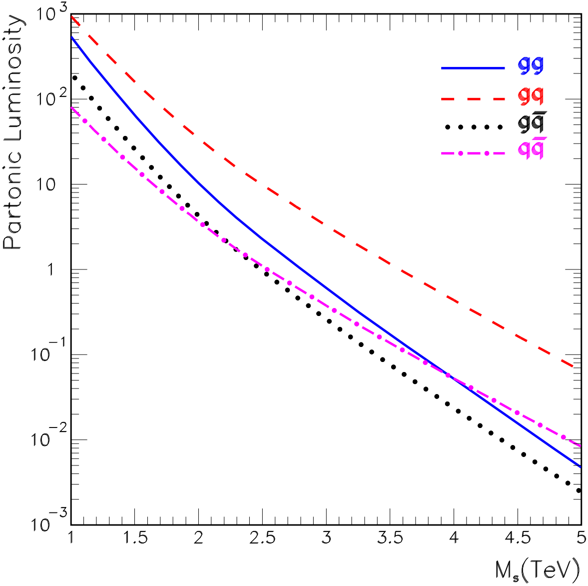
Parton luminosities in pp above TeV

are dominated by gq, gg

$\Rightarrow$ model independent [42]

$gq \to gq$

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



Cross sections

$$|\mathcal{M}(gg \to gg)|^2 \quad , \quad |\mathcal{M}(gg \to q\bar{q})|^2$$

$$|\mathcal{M}(q\bar{q} \to gg)|^2 \quad , \quad |\mathcal{M}(qg \to qg)|^2$$

model independent
for any compactification

Lüst-Stieberger-Taylor '08

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

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

$M_s = 1$

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

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

Energy threshold for black hole production :

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

Horowitz-Polchinski '96, Meade-Randall '07

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

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

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

gauge coupling

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

production of $n \sim 1/g_s^4 \sim 10^4$ string states before reach E_{BH} [28]

SUSY in the bulk?

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

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

very weakly broken (volume suppressed)

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

- Radion $\equiv \ln V_\perp$

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

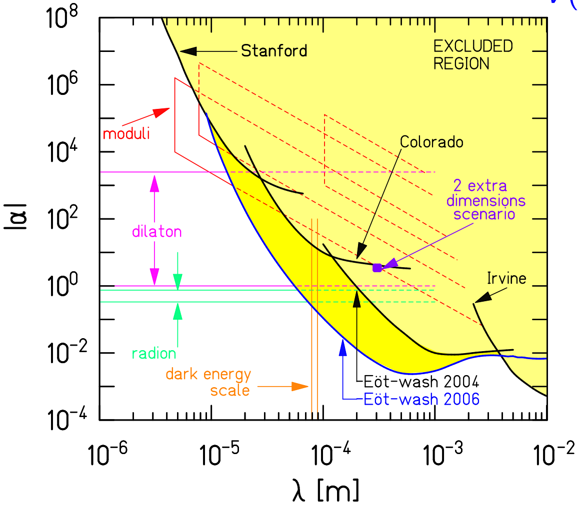
$\Rightarrow$ can be experimentally tested for all $n \geq 2$ [25]

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

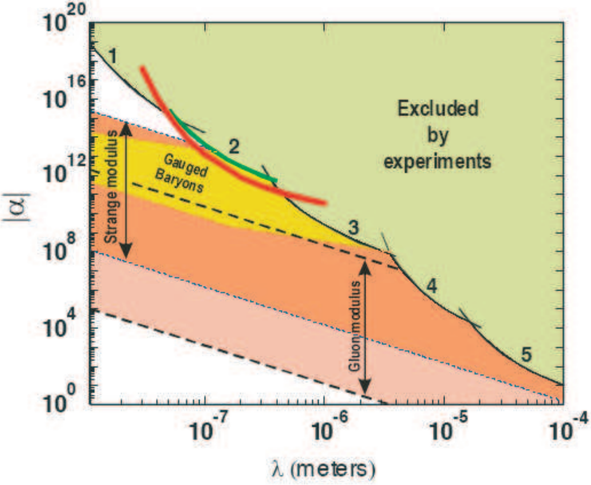
$\Rightarrow$ for the same mass much stronger than gravity: $\gtrsim 10^6$

Experimental limits on short distance forces

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



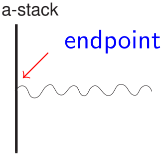
Radion : $M_* \gtrsim 6$ TeV   95% CL   Adelberger et al. '06 an order of magnitude improvement in the range 10-200 nm   Decca et al '07



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

A D-brane embedding of the Standard Model

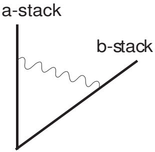
Generic spectrum: N coincident branes $\Rightarrow U(N)$



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

$\Rightarrow$ "baryon" number

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



- oriented strings : need at least 4 brane-stacks

- existence of bulk with large dimensions :

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

color branes (g_3) — weak branes (g_2)

fermion generation $U(3) \times U(2) \times U(1)$

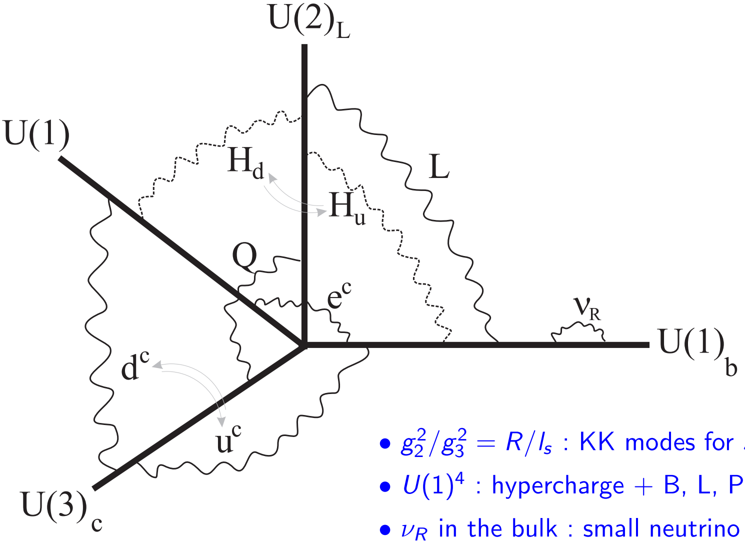
$$
\begin{array}{lll}
Q & (\mathbf{3}, \mathbf{2}; 1, w, 0)_{1/6} & w = \pm 1 \\
u^c & (\bar{\mathbf{3}}, \mathbf{1}; -1, 0, x)_{-2/3} & x = \pm 1, 0 \\
d^c & (\bar{\mathbf{3}}, \mathbf{1}; -1, 0, y)_{1/3} & y = \pm 1, 0 \\
L & (\mathbf{1}, \mathbf{2}; 0, 1, z)_{-1/2} & z = \pm 1, 0 \\
l^c & (\mathbf{1}, \mathbf{1}; 0, 0, 1)_{1} &
\end{array}
$$

hypercharge $Y = c_1 Q_1 + c_2 Q_2 + c_3 Q_3 \Rightarrow$ 2 possibilities:

$$c_3 = -1/3 \quad c_2 = \pm 1/2 \quad x = -1 \quad y = 0 \quad w = \pm 1 \quad z = -1/0$$

$$c_3 = 2/3 \quad c_2 = \pm 1/2 \quad x = 0 \quad y = 1 \quad w = \mp 1 \quad z = -1/0$$

I.A.-Kiritsis-Tomaras '00; I.A.-Kiritsis-Rizos-Tomaras '02



- $g_2^2/g_3^2 = R/l_s$: KK modes for $SU(2)_L$ [30]
- $U(1)^4$: hypercharge + B, L, PQ global
- ν_R in the bulk : small neutrino masses [??]
- $U(1)$ on top of $U(2)$ or $U(3)$ $\Rightarrow$ prediction for $\sin^2\theta_W$ [??]

Conclusions

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

- Well motivated theoretical framework

  with many testable experimental predictions

  new resonances, missing energy

- Stimulus for micro-gravity experiments

  look for new forces at short distances

  higher dim graviton, scalars, gauge fields

But: - unification has to be dropped

- physics is radically changed above string scale

LHC: will explore the physics beyond the Standard Model