Lectures on Extra Dimensions

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1. Motivations and mass hierarchy
2. Strings, branes and extra dimensions (flat and warped)
3. Main experimental signatures
4. Extra U(1)'s
5. Gravity scale and number of species
6. Low string coupling and linear dilaton background

BSM physics: driven by 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? $\Lambda = M_P$ [5]

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

- low scale gravity $\Rightarrow$ large extra dimensions, warped dimensions

- low string scale $\Rightarrow$ low scale gravity, ultra weak string coupling [6]

Experimentally testable framework:

- spectacular model independent predictions

- radical change of high energy physics at the TeV scale

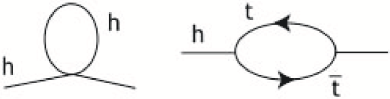
explicit model building is not necessary at this moment

Mass hierarchy problem

Higgs mass: very sensitive to high energy physics

1-loop radiative corrections:

dominant contributions:



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

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 $\mu^2_{\rm bare}$ and radiative corrections

order by order

Mass hierarchy problem

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

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

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

- 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 : $10^{-2}\Lambda^2 \lesssim 10^4\ ({\rm GeV})^2 \Rightarrow \Lambda \lesssim 1$ TeV

  → new physics within LHC range ! [2]

Newton's law

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

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

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

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

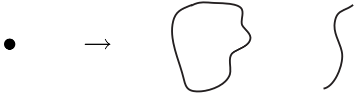
At what energy gravitation becomes comparable to the other interactions?

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

10^{15} × the LHC energy! [2] [12]

String theory: Quantum Mechanics + General Relativity

point particle → extended objects



$\Rightarrow$ particles $\equiv$ string vibrations

Framework for unification of all interactions

Mass scale: string tension $M_{\rm s} \leftrightarrow$ string size: $l_{\rm s}$

Consistent theory : 9 spatial dimensions !

six new dimensions of space

matter and gauge interactions may be localized in less than 9 dims $\Rightarrow$

our universe on a *p*-brane ? [10]

extended in p spatial dimensions $p = 0$: particle, $p = 1$: string,…

Extra Dimensions

how they escape observation?

finite size R Kaluza and Klein 1920

energy cost to send a signal:

$E > R^{-1}$ ← compactification scale

experimental limits on their size

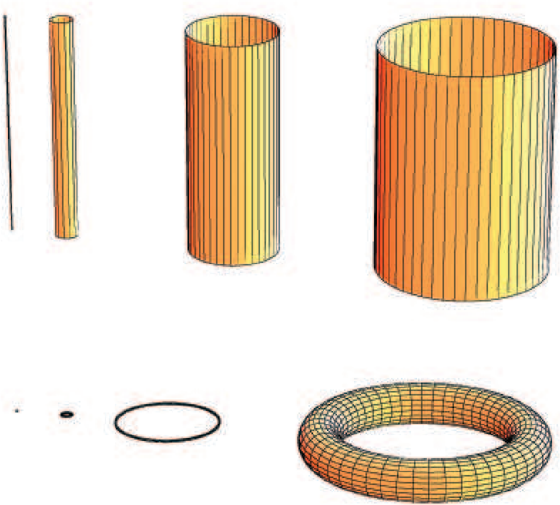
light signal : $E \gtrsim 1$ TeV

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

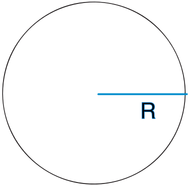
how to detect their existence?

motion in the internal space ⇒ mass spectrum in 3d

Dimensions D=??



example: - one internal circular dimension
- light signal



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

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

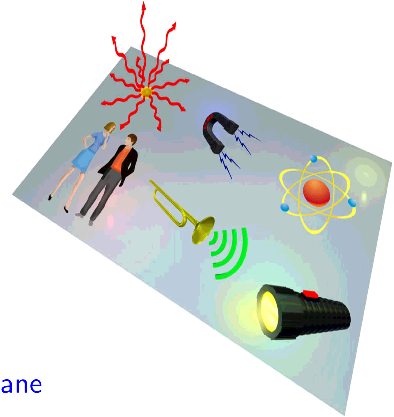
$\Rightarrow$ 3d: tower of Kaluza Klein particles with masses $M_n = n/R$

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

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

$\Leftrightarrow$ propagation in the internal space [6]

Our universe on a membrane

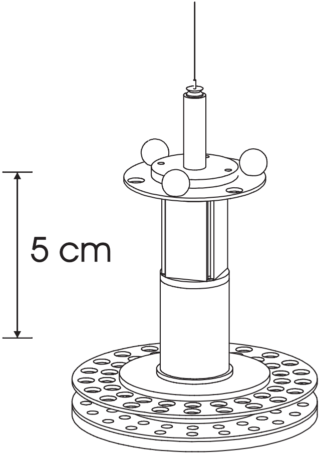


Two types of new dimensions:

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

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

Adelberger et al. '06



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

- dark-energy length scale $\approx 85\mu\text{m}$ [21]

Low scale gravity

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

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

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

n dimensions of size $R_\perp$

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

excluded [53]

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

possible

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

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

  however for $< R_\perp$: gravity (3+n)d [14]

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

10^{30} times stronger than thought previously! [15]

Low scale gravity

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

total force = observed force × volume $\perp$

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

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

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

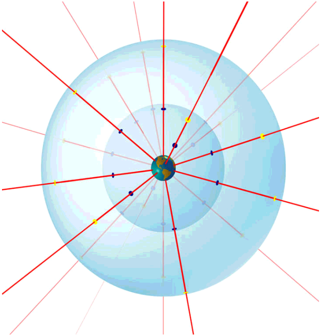
n dimensions of size $R_\perp$

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

$\Rightarrow 1 = E^2/M_P^2 \times (R_\perp E)^n$ for $E = M_* \simeq 1$ TeV

Gravity modification at submillimeter distances

Newton's law: force decreases with area



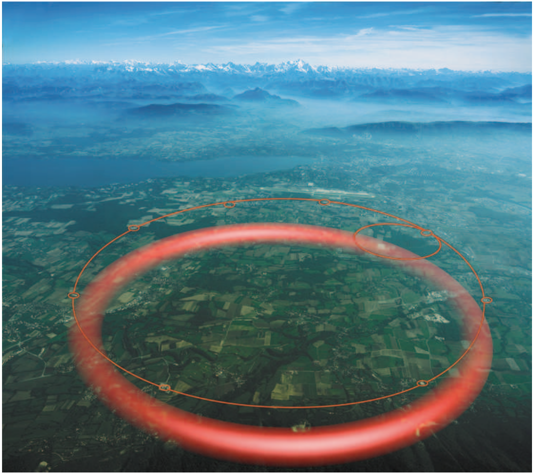
3d: force $\sim 1/r^2$

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

observable for $n = 2$: $1/r^4$ with $r << .1$ mm [12]

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

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

High string scale

perturbative heterotic string : the most natural for SUSY and unification

gravity and gauge interactions have same origin

massless excitations of the closed string

But mismatch between string and GUT scales:

$M_s = g_H\, M_P \simeq 50\, M_{\rm GUT}$ $\qquad g_H^2 \simeq \alpha_{\rm GUT} \simeq 1/25$ [21]

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

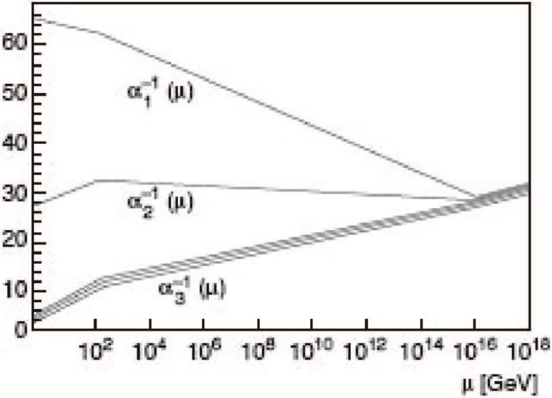
introduce large threshold corrections or strong coupling $\rightarrow$ $M_s \simeq M_{\rm GUT}$

but loose predictivity

Gauge coupling unification

Energy evolution of gauge couplings $\alpha_i = g_i^2/4\pi \Rightarrow$

low energy data $\longrightarrow$ extrapolation at high energies:



unification at $M_{GUT} \simeq 10^{15} - 10^{16}$ GeV

Intersecting branes: ‘perfect’ for SM embedding

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

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

however GUTs: problematic:

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

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

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

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

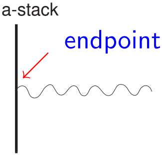
→ Non-perturbative M/F-theory models:

combine good properties of heterotic and intersecting branes

but lack exact description for systematic studies

D-brane embedding of the Standard Model

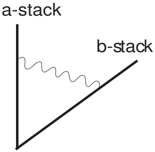
Generic spectrum: N coincident branes $\Rightarrow U(N)$



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



non-oriented strings $\Rightarrow$ also:

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

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

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

$M_p^2 \simeq \frac{1}{g_s^2} M_s^{2+n} R_{\perp}^n$ $g_s = \alpha$: weak string coupling [17]

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

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

$M_s \sim 1$ TeV $\Rightarrow R_{\perp}^n = 10^{32}\, l_s^n$ [49] [50]

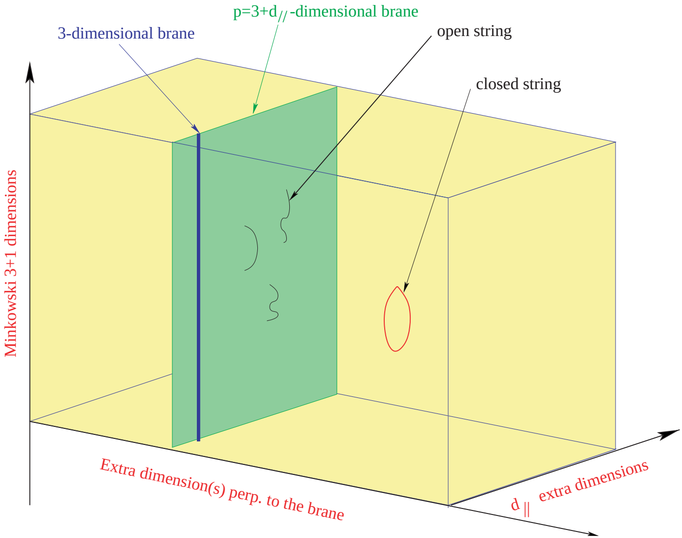
$R_{\perp} \sim .1 - 10^{-13}$ mm for $n = 2-6$ [11]

distances $< R_{\perp}$: gravity $(4+n)$-dim $\longrightarrow$ strong at 10^{-16} cm [23]

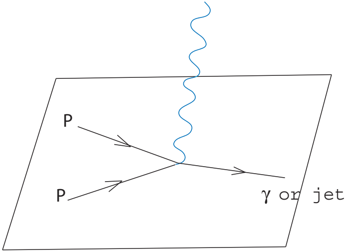
Braneworld

2 types of compact extra dimensions:

- parallel ($d_{\|}$): $\lesssim 10^{-16}$ cm (TeV) [26]
- transverse ($\perp$): $\lesssim 0.1$ mm (meV) [40]



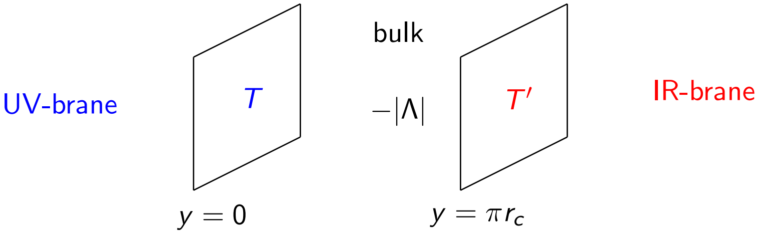
Gravitational radiation in the bulk ⇒ missing energy



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}
NLC	1.2×10^{-2}	1.2×10^{-9}	6.5×10^{-12}

Randal Sundrum models

spacetime = slice of AdS$_5$: $ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$ $k^2 \sim \Lambda/M_5^3$



bulk

UV-brane

T

$-|\Lambda|$

T'

IR-brane

$y = 0$

$y = \pi r_c$

- 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 [51] [52]

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

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

Other accelerator signatures

- Large TeV dimensions seen by SM gauge interactions

  ⇒ KK resonances of SM gauge bosons [22] I.A. '90

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

- string physics and possible strong gravity effects

  Massive string vibrations ⇒ e.g. resonances in dijet distribution [34] [36]

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

  higher spin excitations of quarks and gluons with strong interactions

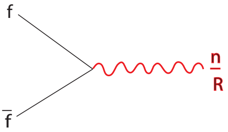
  Anchordoqui-Goldberg-Lüst-Nawata-Taylor-Stieberger '08

  production of micro-black holes? [38]

  Giddings-Thomas, Dimopoulos-Landsberg '01

Localized fermions (on 3-brane intersections) [40]

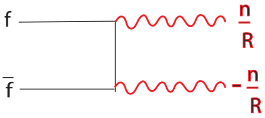
⇒ single production of KK modes I.A.-Benakli '94



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

Otherwise KK momentum conservation [30]

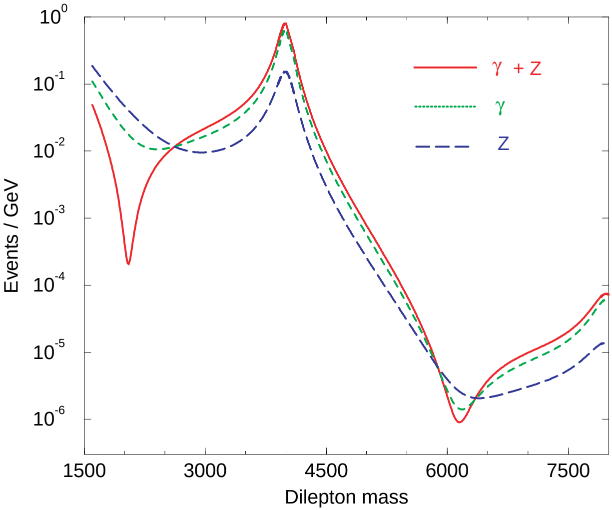
⇒ pair production of KK modes (universal dims)



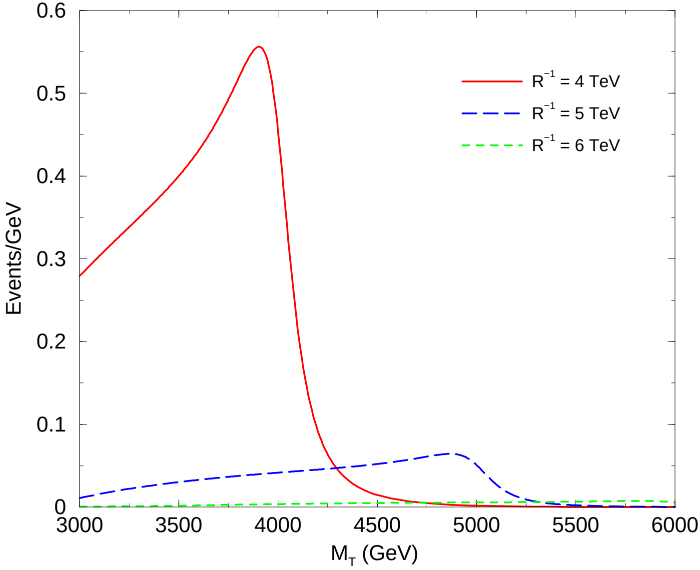
- weak bounds $R^{-1} \gtrsim$ 300-500 GeV
- no resonances
- lightest KK stable : dark matter candidate

Servant-Tait '02

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



KK W-production at LHC in the $l\nu$ channel [27]

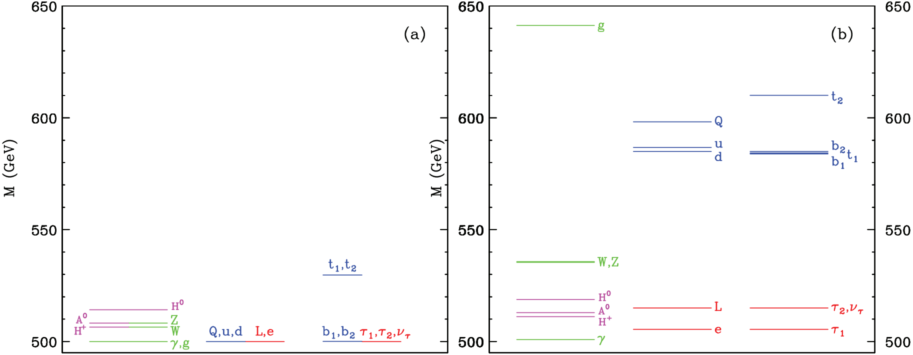


Mass spectrum

Radiative corrections $\Rightarrow$ mass shifts that lift degeneracy at lowest KK level

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

Cheng-Matchev-Schmaltz '02



UED hadron collider phenomenology

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

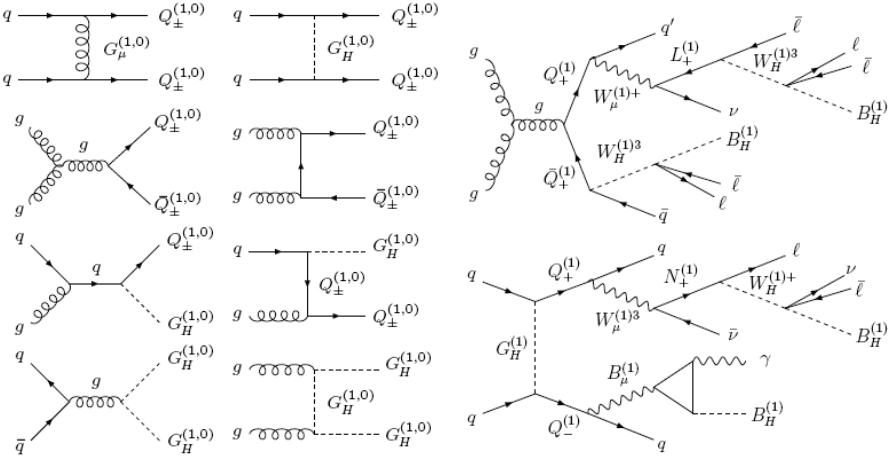
  LHC: 1-100 pb for $R^{-1} \lesssim 800$ GeV
- cascade decays via KK-W bosons and KK-leptons

  determine particle properties from different distributions
- missing energy from LKP: weakly interacting escaping detection
- phenomenology similar to supersymmetry [33]

  spin determination important for distinguishing SUSY and UED [26]

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

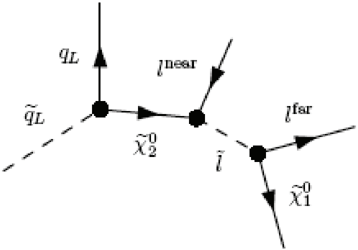
Production at LHC



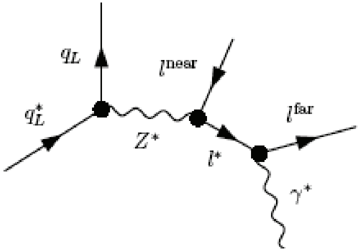
SUSY vs UED signals at LHC

Example: jet dilepton final state [31]

SUSY



UED



Massive string vibrations

indirect effects: virtual exchanges ⇒ effective interactions

e.g. four-fermion operators

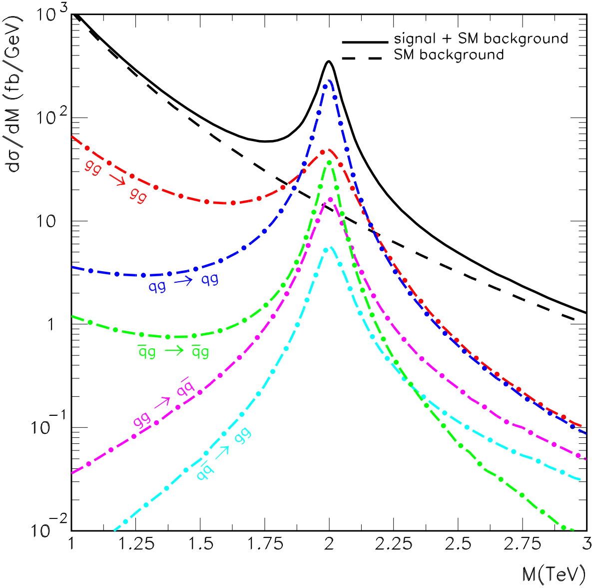
Actual limits: Matter fermions on

- same set of branes ⇒ $M_s \gtrsim 500$ 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 ⇒ direct production: string physics

Universal deviation from Standard Model in dijet distribution



$M_s = 2$ TeV

Width = 15-150 GeV

Anchordoqui-Goldberg-Lüst-Nawata-Taylor-Stieberger '08 [26]

present LHC limits (2010 data): $M_s \gtrsim 2.5$ TeV

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

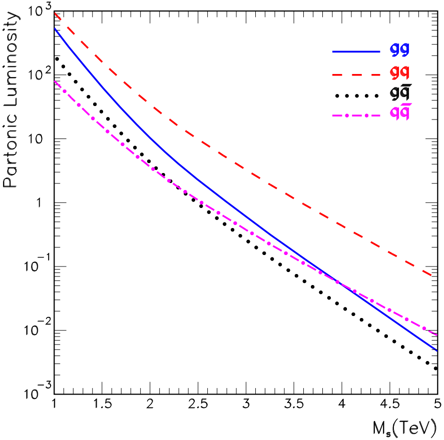
Universal sum over infinite exchange of string (Regge) excitations [26]

Parton luminosities in pp above TeV

are dominated by gq, gg

$\Rightarrow$ model independent

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



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

Lüst-Stieberger-Taylor '08

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

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

$M_s = 1$

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

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

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 $M_{\rm BH}$

Other accelerator signatures

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

  masses suppressed by a loop factor

  new Chern-Simons type interactions

  usually associated to known global symmetries of the SM

  (anomalous or not) such as (combinations of)

  Baryon and Lepton number, or PQ symmetry

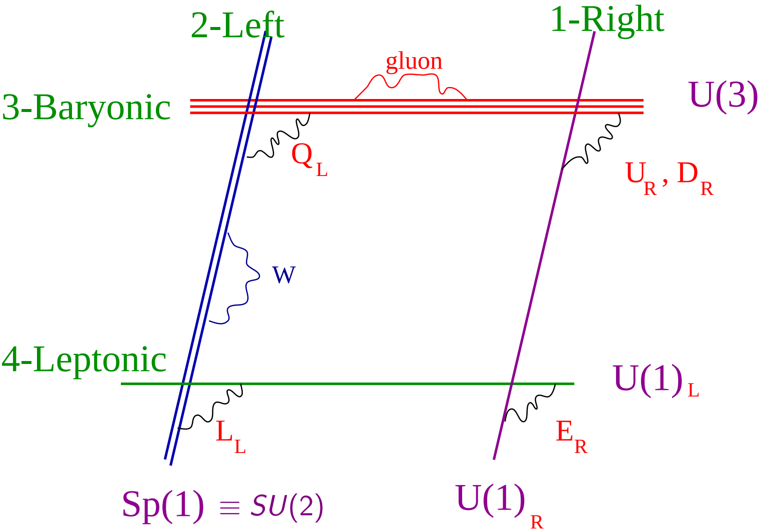
  Two kinds of massive $U(1)$'s: I.A.-Kiritsis-Rizos '02

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

Standard Model on D-branes



$U(1)^3$: hypercharge + B, L global [45]

global symmetries

- B and L become massive due to anomalies

  Green-Schwarz terms

- the global symmetries remain in perturbation

  - Baryon number $\Rrightarrow$ proton stability

  - Lepton number $\Rrightarrow$ protect small neutrino masses

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

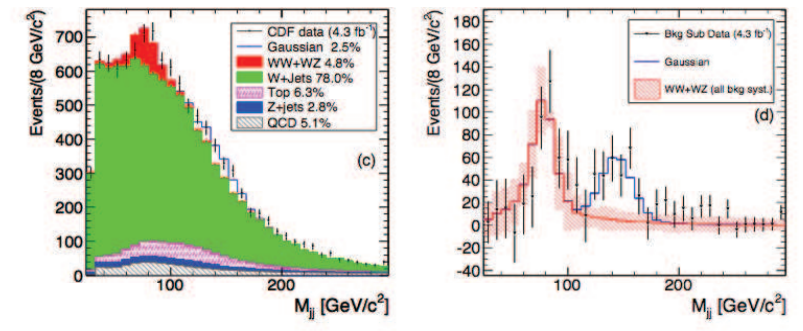
- $B, L \Rrightarrow$ extra Z's

  with for instance leptophobic couplings leading to CDF-type events [21]

  Anchordoqui-I.A.-Goldberg-Huang-Lüst-Taylor to appear

"Bump" in W+2jet events - CDF

- **Routine measurement of WW to lνjj cross section led to deviations between predicted by ALPGEN background and data around 145 GeV**
- **"Excess" could be described by signal with Gaussian shape with cross section of ~4 pb**



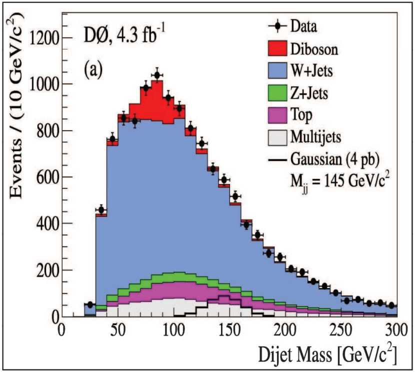
- **What is this**
  - **Mis-modelling of Standard Model background?**
  - **Hints of new particle with mass of ~145 GeV decaying to two jets?**

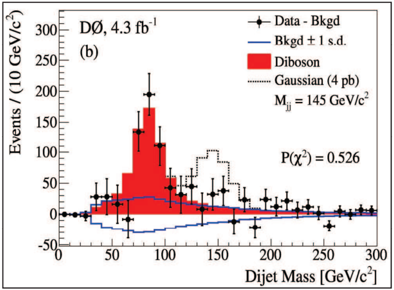
Dmitri Denisov, Erice, June 2011

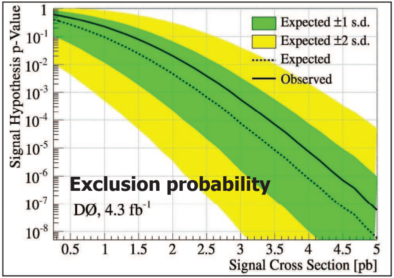
18

“Bump” in W+2jet events - DØ

- **DØ repeated analysis with exactly the same selections as CDF**
- **No evidence of resonance near to 145 GeV observed**
  - **Limits set**
- **Importance of the two experiments**

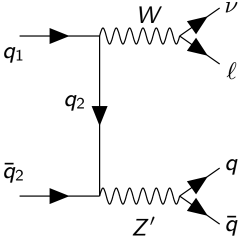






possible explanation: Z' in D-brane models

Anchordoqui-Goldberg-Huang-Lüst-Taylor '11



Required properties: leptophobic, no mixing with Z after EW symmetry breaking, much lighter than M_s

Good candidate: anomalous Baryon number $U(1)_B$

$U(3) \times SU(2) \times U(1)_L \times U(1)_R$ D-brane model [40]

3 natural $U(1)$'s: $Y, B, B-L$

R-neutrino $\Rightarrow$ $B-L$ anomaly free $\Rightarrow$ natural heavier than B

In general: 3×3 rotation matrix $\Rightarrow$ 6 parameters: 3 couplings + 3 angles

4 parameters are fixed by the SM: 2 couplings and 2 angles

from hypercharge combination $Y = \frac{1}{2}(B - L + Q_{1R})$

remaining 2 fixed by phenomenological constraints:

leptophobic $\lesssim 1\%$, no mixing with Z,

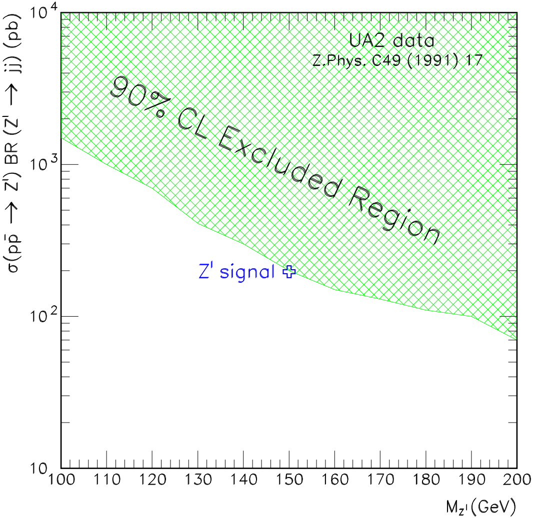
$\sigma(p\bar{p} \to WZ') \times \mathrm{BR}(Z' \to jj) \lesssim 1.9\ \mathrm{pb}$ at $\sqrt{s} = 1.96\ \mathrm{TeV}$,

UA2 upper limit on $\sigma(p\bar{p} \to Z') \times \mathrm{BR}(Z' \to jj)$ at $\sqrt{s} = 630\ \mathrm{GeV}$

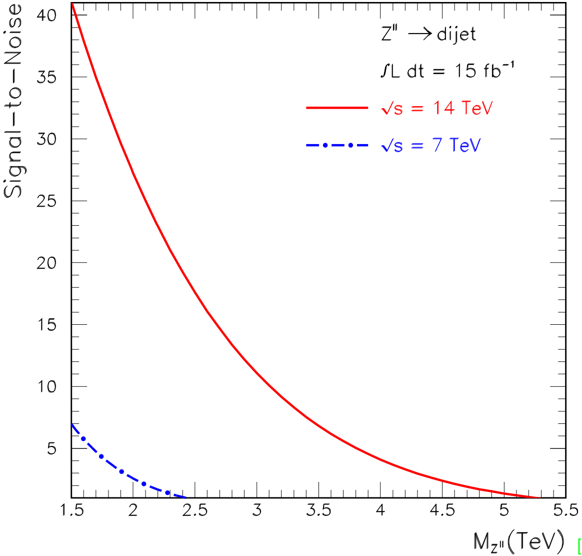
further predictions: Z'' [47] γ+jet ($gg \to \gamma g$ from Y component on color stack)

Bounds on Z's from direct production at UA2

$p\bar{p} \to Z' \to jj$ at $\sqrt{s} = 640$ GeV

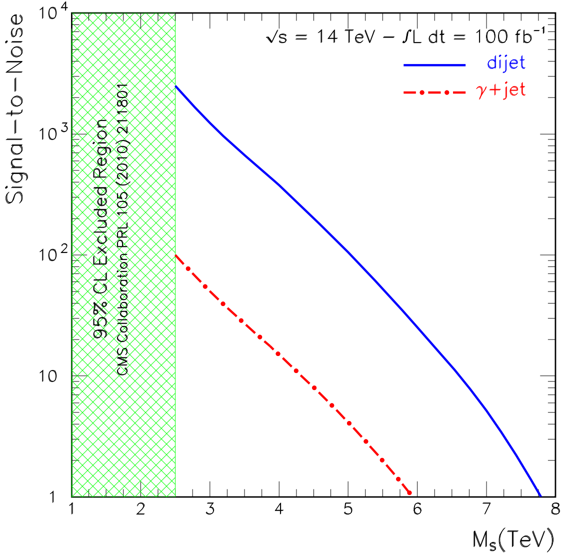


Dijet signals of Z'' at the LHC



[45]

$pp \longrightarrow$ dijet vs $pp \longrightarrow \gamma$ jet at LHC



[21]

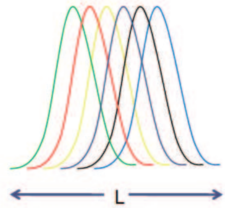
More general framework: large number of species

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

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

2 ways to realize $N = 10^{32}$ lowering the string scale

1. Large volume compactifications SM on D-branes [21]

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

2. $N \sim$ effective number of string modes contributing to the BH bound

   Dvali-Lüst '09, Dvali-Gomez '10

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

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

   in this case gravity does NOT become strong at M_s

Both ways are compatible with the general string relation:

$$M_p^2 = \frac{1}{g_s^2} V_6 \, M_s^8$$

V_6 : internal $6d$ compactification volume

Gauge/Gravity duality ⇛ toy 5d bulk model

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

Analogy from D3-branes : AdS_5

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

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

Aharony-Berkooz-Kutasov-Seiberg '98

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

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

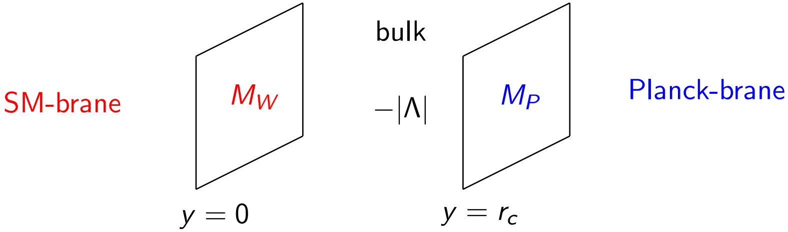
$$S_{vis(hid)} = \int d^4x \sqrt{-g}\, e^{-\Phi} \left(L_{SM(hid)} - T_{vis(hid)}\right)$$

Tuning conditions: $T_{vis} = -T_{hid} \leftrightarrow \Lambda < 0$ [24]

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

$g_s^2 = e^{-\alpha|y|}$; $ds^2 = e^{\frac{2}{3}\alpha|y|}\left(\eta_{\mu\nu}dx^\mu dx^\nu + dy^2\right)$ ← Einstein frame [24]

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



- exponential hierarchy: $g_s^2 = e^{-\alpha|y|}$ $M_P^2 \sim \frac{M_5^3}{\alpha} e^{\alpha r_c}$ $\alpha \equiv k_{RS}$
- 4d graviton flat, KK gravitons localized near SM
- SM particles cannot be in the bulk

bulk gauge bosons: exp suppressed couplings

LST KK graviton phenomenology

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

  $\Rightarrow$ 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

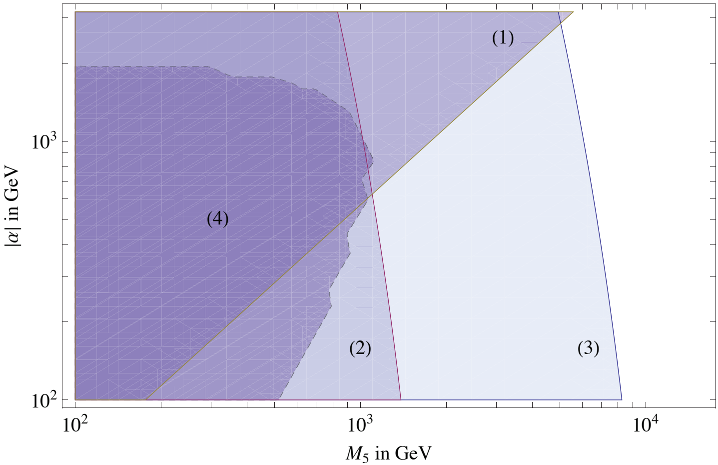
  $\Rightarrow$ narrow resonant peaks in di-lepton or di-jet channels

- extrapolates between RS and flat extra dims ($n = 1$) [12]

  $\alpha \gtrsim (0.1\,\mathrm{mm})^{-1} \sim 10^{-2}$ eV from microgravity experiments

  $\Rightarrow$ distinct experimental signals

Bounds on the LST parameter space



exclusion by (1) perturbativity (2) Tevatron with 5.4 fb^{-1} data

(3) LHC 14 TeV with 10 fb^{-1} (4) diphoton at Tevatron 5.4 fb^{-1}

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