Extra dimensions and Braneworlds

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Summer School on the Standard Model and Beyond

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- Mass hierarchy, low energy SUSY and 126 GeV Higgs
- Live with the hierarchy
- Low scale strings and extra dimensions

particle listing

H^0 (Higgs Boson)

The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

H^0 MASS

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
125.9±0.4 OUR AVERAGE				
125.8±0.4±0.4	[1] CHATRCHYAN	13J	CMS	pp, 7 and 8 TeV
126.0±0.4±0.4	[2] AAD	12AI	ATLS	pp, 7 and 8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
126.2±0.6±0.2	[3] CHATRCHYAN	13J	CMS	pp, 7 and 8 TeV
125.3±0.4±0.5	[4] CHATRCHYAN	12N	CMS	pp, 7 and 8 TeV

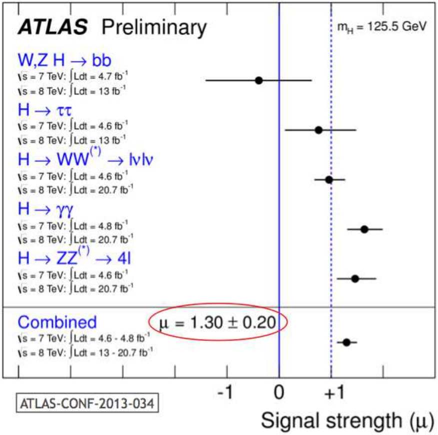
HTTP://PDG.LBL.GOV Page 1 Created: 7/31/2013 summary tables

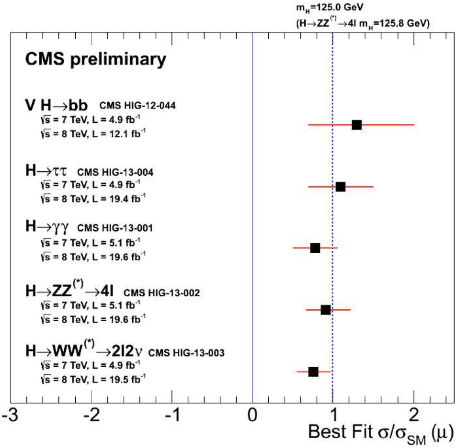
$\boldsymbol{H^0}$ Mass $m = 125.9 \pm 0.4$ GeV

$\boldsymbol{H^0}$ signal strengths in different channels [n]

Combined Final States $= 1.07 \pm 0.26 \quad (S = 1.4)$
$W W^*$ Final State $= 0.88 \pm 0.33 \quad (S = 1.1)$
$Z Z^*$ Final State $= 0.89^{+0.30}_{-0.25}$
$\gamma\gamma$ Final State $= 1.65 \pm 0.33$
$b\bar{b}$ Final State $= 0.5^{+0.8}_{-0.7}$
$\tau^+\tau^-$ Final State $= 0.1 \pm 0.7$

Couplings of the new boson vs SM





exclusion : spin 2 and pseudoscalar at $\gtrsim$ 95% CL

Agreement with Standard Model expectation at $\sim 2\,\sigma$

Quantum Field Theory + Gauge Invariance

Very accurate description of Particle Physics at present energies

$$\mathcal{L}_{\rm SM} = -\frac{1}{2}{\rm tr}F_{\mu\nu}^2 + \bar\psi \not{D}\psi + \bar\psi YH\psi - |DH|^2 - V(H)$$

Three sectors: Forces Matter Higgs

1. Forces: uniquely determined by geometry (given the gauge group)
2. Matter: fixed by the representations (discrete arbitrariness)
3. Scalar Higgs sector: arbitrary (no guidance)

   experiment $\Rightarrow$ minimal: $V(H) = -\mu^2|H|^2 + \lambda\left(|H|^2\right)^2$ Why?

   μ: the only relevant operator creating the hierarchy problem

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

Higgs mass: very sensitive to high energy physics

quantum corrections: $\delta m_H \sim \delta M_W$ of order of UV cutoff Λ

or in general the scale of new physics/massive particles

stability requires adjustment of parameters at very high accuracy

to keep the physical mass $(m_H^{tree})^2 + \delta m_H^2$ at the weak scale

$\Lambda = M_{GUT}$ or $M_P \Rightarrow$ fine tuning at 28-32 decimal places !

Why gravity is so weak compared to the other interactions ?

Newton's law

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

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 ! [39]

Many more unanswered questions

- Quantize gravity
- Charge quantization
- Origin of Dark matter [10]
- Origin of Dark energy
- Baryon asymmetry in the Universe
- Origin of neutrino masses

  New states, beyond Higgs mechanism, lepton number violation ?
- Unification of gauge couplings ? [11]

(Hyper)charge quantization

All color singlet states have integer charges Why?

$SU(3) \times SU(2) \times U(1)_Y \qquad Q = T_3 + Y$

$$\begin{aligned} q &= (3,2)_{1/6} \\ u^c &= (\bar{3},1)_{-2/3} \\ d^c &= (\bar{3},1)_{1/3} \\ \ell &= (1,2)_{-1/2} \\ e^c &= (1,1)_{1} \end{aligned}$$

$$q = \begin{pmatrix} u_{2/3} \\ d_{-1/3} \end{pmatrix} \qquad \ell = \begin{pmatrix} \nu_0 \\ e_{-1} \end{pmatrix}$$

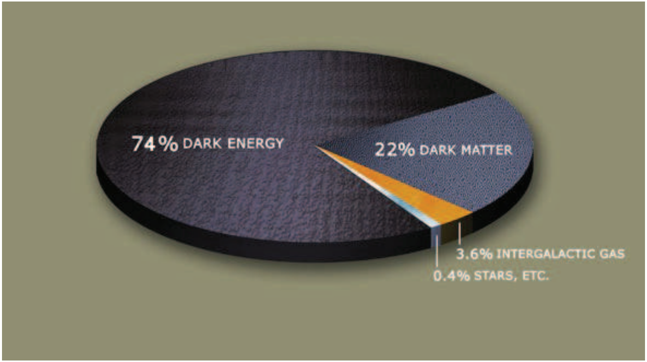
In a non-abelian theory charges are quantized

e.g. $SU(2)$: T_3 eigenvalues are $1/2$-integers

What our Universe is made of ?

- Ordinary matter: only a tiny fraction
- Non-luminous (dark) matter: $\sim 25\%$

  Natural explanation: new stable Weakly Interacting Massive Particle
  in the LHC energy region
- Unknown relativistic dark energy: $\sim 70\%$ [8]

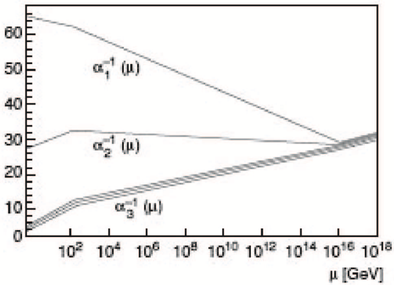


Gauge coupling unification

Energy evolution of gauge couplings $\alpha_i = \dfrac{g_i^2}{4\pi}$:

$$\frac{d\alpha_i}{d\ln Q} = -\frac{b_i}{2\pi}\alpha_i^2 \quad \Rightarrow \quad \alpha_i^{-1}(Q) = \alpha_i^{-1}(Q_0) - \frac{b_i}{2\pi}\ln\frac{Q}{Q_0}$$

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



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

Standard picture: low energy supersymmetry

every particle has a superpartner with spin differ by $1/2$

cancel large quantum corrections to the Higgs mass

$\Rightarrow$ superpartner mass splittings must be not far from the weak scale

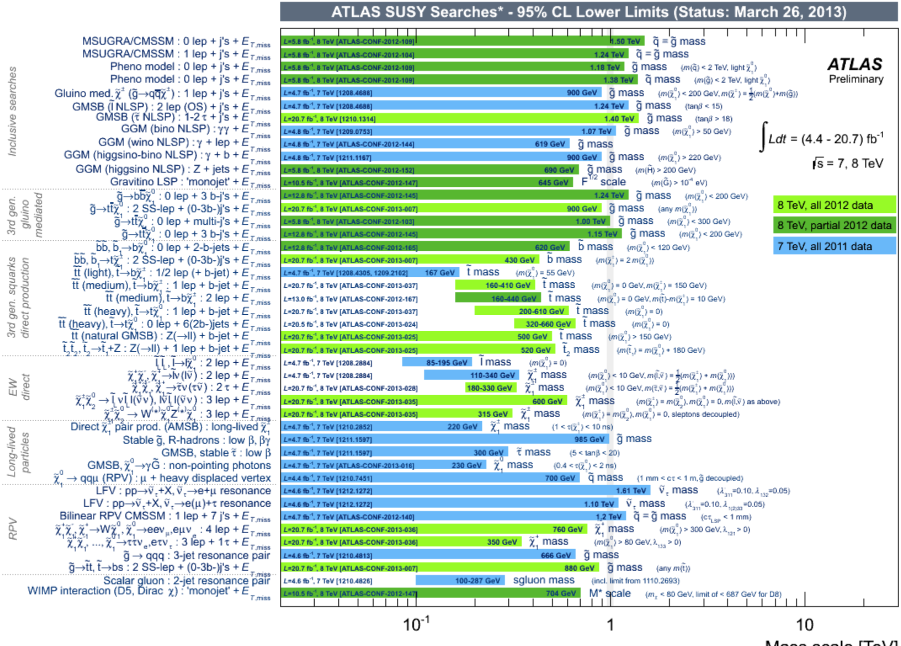
Advantages:

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

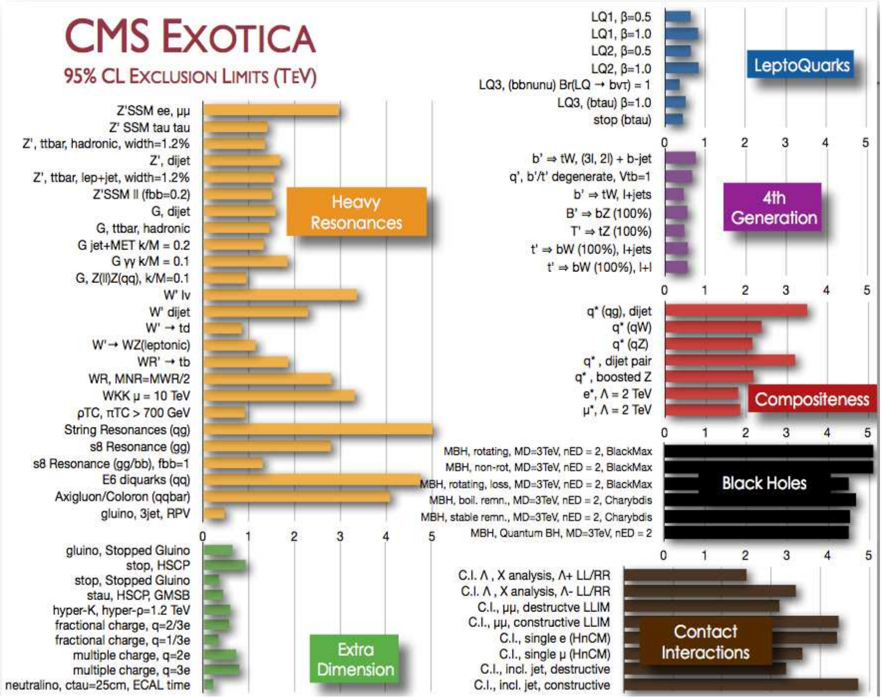
Problems:

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

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



*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)
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
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
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
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
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

Remarks on the value of the Higgs mass ~ 126 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

Window to new physics ?

- compatible with supersymmetry

  but appears fine-tuned in its minimal version [17]

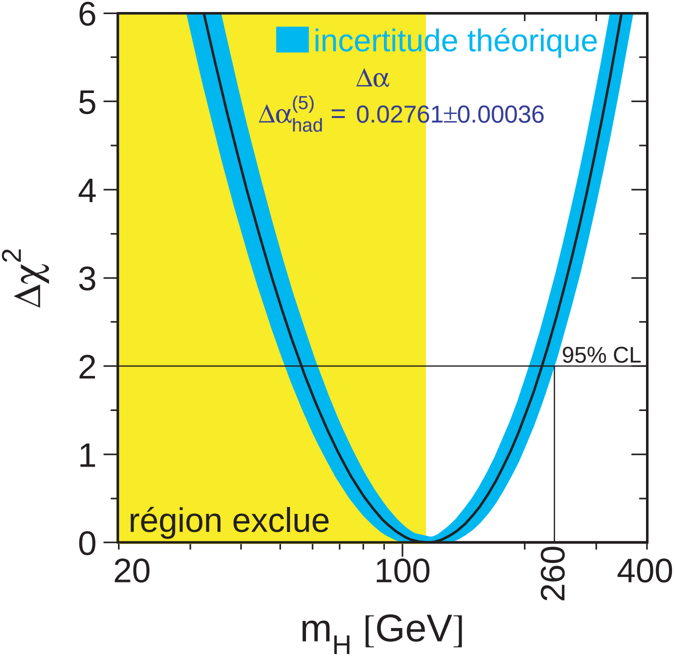
  early to draw a general conclusion before LHC13/14

  e.g. an extra singlet or split families can alleviate the fine tuning

- very important to measure its properties and couplings

  any deviation of its couplings to top, bottom and EW gauge bosons

  implies new light states involved in the EWSB altering the fine-tuning



incertitude théorique
Δα
$\Delta\alpha^{(5)}_{had} = 0.02761 \pm 0.00036$
95% CL
région exclue
$\Delta\chi^2$
0
1
2
3
4
5
6
20
100
260
400
m_H [GeV]

Fine-tuning in MSSM

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

RG evolution: $m_2^2 = \; m_2^2(M_{\rm GUT}) - \dfrac{3\lambda_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln \dfrac{M_{\rm GUT}}{m_{\tilde{t}}} + \cdots$ [27]

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

Reduce the fine-tuning

- minimize radiative corrections

  $M_{\rm GUT} \to \Lambda$: low messenger scale (gauge mediation)

  $$\delta m_{\tilde{t}} = \frac{8\alpha_s}{3\pi} M_3^2 \ln \frac{\Lambda}{M_3} + \cdots$$

- extend the MSSM

  extra fields beyond LHC reach $\to$ effective field theory approach

- $\cdots$

MSSM with dim-5 and 6 operators

I.A.-Dudas-Ghilencea-Tziveloglou '08, '09, '10

parametrize new physics above MSSM by higher-dim effective operators

relevant super potential operators of dimension-5:

$$\mathcal{L}^{(5)} = \frac{1}{M} \int d^2\theta \, (\eta_1 + \eta_2 S) \, (H_1 H_2)^2$$

η_1 : generated for instance by a singlet

$$W = \lambda\sigma H_1 H_2 + M\sigma^2 \quad \rightarrow \quad W_{\rm eff} = \frac{\lambda^2}{M} \, (H_1 H_2)^2$$

Strumia '99 ; Brignole-Casas-Espinosa-Navarro '03
Dine-Seiberg-Thomas '07

η_2 : corresponding soft breaking term spurion $S \equiv m_S \, \theta^2$

Physical consequences of MSSM$_5$: Scalar potential

$$\mathcal{V} = m_1^2|h_1|^2 + m_2^2|h_2|^2 + B\mu(h_1 h_2 + \mathrm{h.c.}) + \frac{g_2^2 + g_Y^2}{8}\left(|h_1|^2 - |h_2|^2\right)^2$$
$$+ \left(|h_1|^2 + |h_2|^2\right)\left(\eta_1 h_1 h_2 + \mathrm{h.c.}\right) + \frac{1}{2}\left[\eta_2 (h_1 h_2)^2 + \mathrm{h.c.}\right]$$
$$+ \eta_1^2 \, |h_1 h_2|^2 \left(|h_1|^2 + |h_2|^2\right)$$

- $\eta_{1,2} \Rightarrow$ quartic terms along the D-flat direction $|h_1| = |h_2|$
- tree-level mass can increase significantly
- bigger parameter space for LSP being dark matter

Bernal-Blum-Nir-Losada '09

- last term $\sim \eta_1^2$: guarantees stability of the potential

but requires addition of dim-6 operators

MSSM Higss with dim-6 operators

dim-6 operators can have an independent scale from dim-5

Classification of all dim-6 contributing to the scalar potential

(without $\text{SU}\not{\text{S}}\text{Y}$) $\Rightarrow$

large $\tan\beta$ expansion: $\delta_6 m_h^2 = f\, v^2 + \cdots$

constant receiving contributions from several operators

$f \sim f_0 \times \left(\mu^2/M^2,\ m_S^2/M^2,\ \mu m_S/M^2,\ v^2/M^2\right)$

$m_S = 1$ TeV, $M = 10$ TeV, $f_0 \sim 1 - 2.5$ for each operator

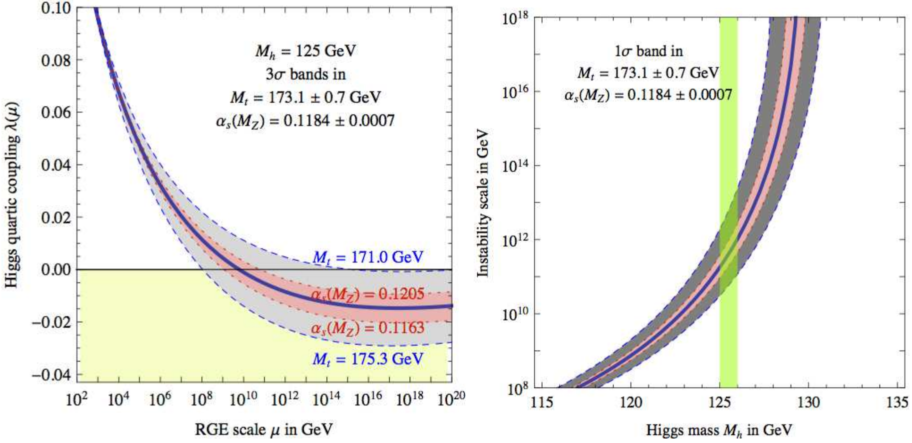
$\Rightarrow m_h \simeq 103 - 119$ GeV

$\Rightarrow$ MSSM with dim-5 and dim-6 operators:

possible resolution of the MSSM fine-tuning problem

Can the SM be valid at high energies?

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



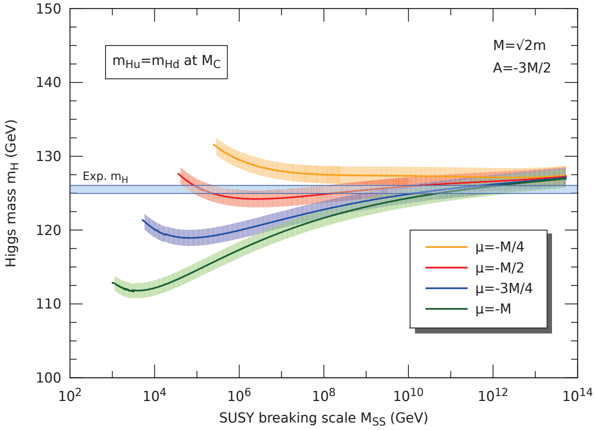
Instability of the SM Higgs potential $\Rightarrow$ metastability of the EW vacuum

SUSY : $\lambda = 0 \Rightarrow \sin\beta = 1$

$H_{SM} = \sin\beta\, H_u - \cos\beta\, H_d^*$ $\qquad$ $\lambda = \frac{1}{8}(g_2^2 + g'^2)\cos^2 2\beta$

$\lambda = 0$ at a scale $\geq 10^{10}$ GeV $\Rightarrow m_H = 126 \pm 3$ GeV

Ibanez-Valenzuela '13



e.g. for universal $\sqrt{2}m = M = M_{SS},\ A = -3/2M$

If the weak scale is tuned $\Rightarrow$ 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 $\Rightarrow$ 'mini' split

  $m_S \sim$ few - thousands TeV

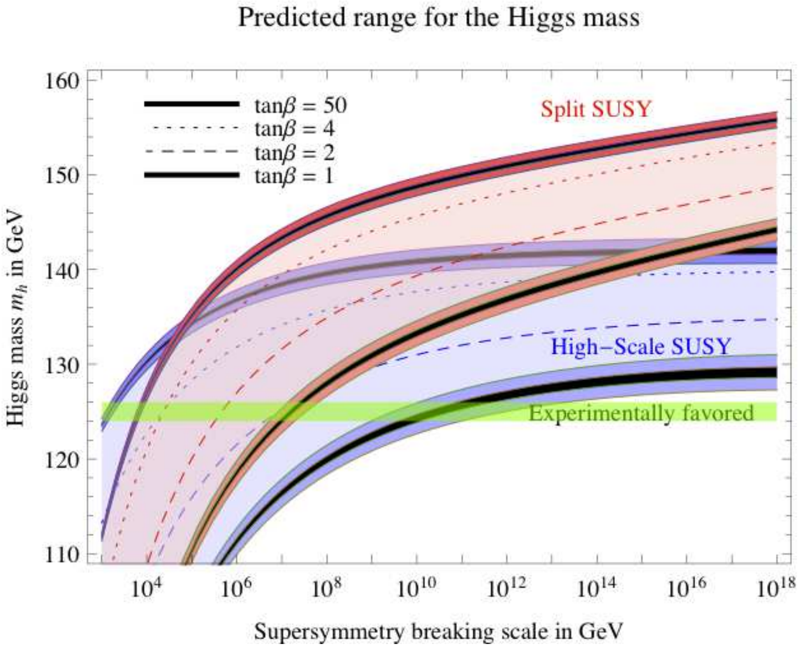
  gauginos: a loop factor lighter than scalars ($\sim m_{3/2}$)
- natural string framework: intersecting (or magnetized) branes

  IA-Dimopoulos '04

  D-brane stacks are supersymmetric with massless gauginos

  intersections have chiral fermions with broken SUSY & massive scalars

Giudice-Strumia '11



An extra $U(1)$ can also cure the instability problem

Anchordoqui-IA-Goldberg-Huang-Lüst-Taylor-Vlcek '12

usually associated to known global symmetries of the SM: $B, L, \ldots$

- B anomalous and superheavy
- $B-L$ massless at the string scale (no associated 6d anomaly)

  but broken at TeV by a scalar VEV with the quantum numbers of N_R
- L-violation from higher-dim operators suppressed by the string scale
- $U(3)$ unification, Y combination $\Rightarrow$ 2 parameters: 1 coupling + $m_{Z''}$
- perturbativity $\Rightarrow 0.5 \lesssim g_{U(1)_R} \lesssim 1$
- interesting LHC phenomenology and cosmology

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

Experimentally testable framework:

- 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 $\times \Lambda^2$ [46]

But unification has to be probably dropped

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

Strings and extra dimensions

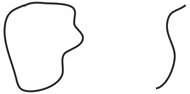
Standard Model of electroweak + strong Interactions :

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

String theory :

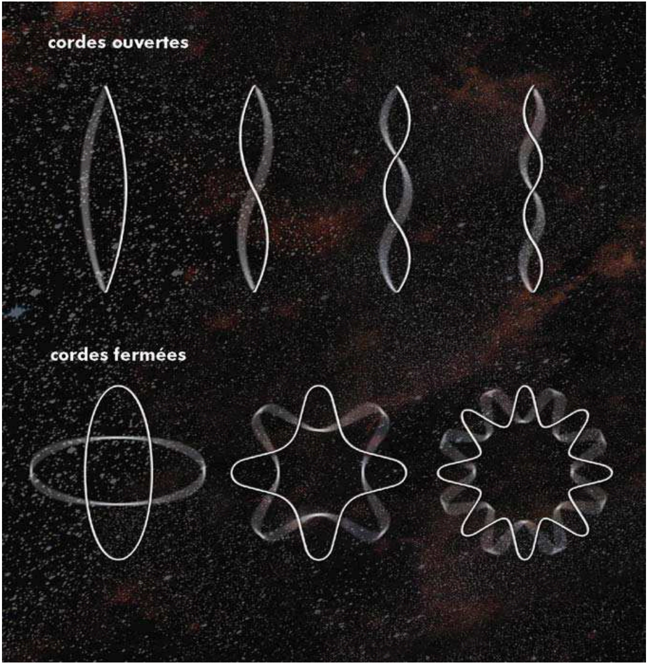
- Quantum Mechanics + General Relativity

point particle $\to$ extended objects

$\bullet \quad \to$  $\Rightarrow$ particles $\equiv$ string vibrations

Framework for unification of all interactions

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


cordes ouvertes
cordes fermées

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 ? [34]

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

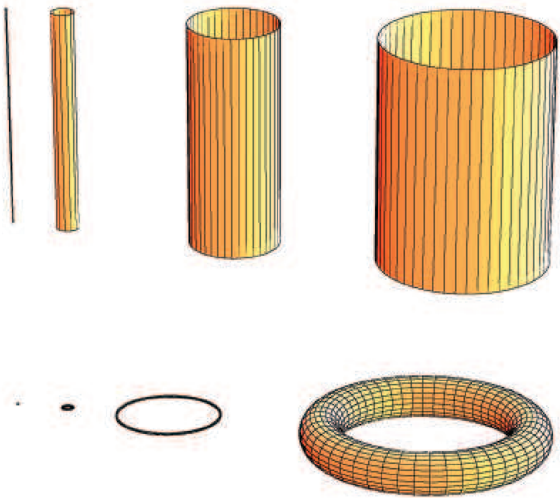
light signal $\Rightarrow$ $E \gtrsim 1$ TeV

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

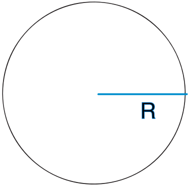
how to detect their existence?

motion in the internal space $\Rightarrow$ mass spectrum in 3d

Dimensions D=??



example: - one internal circular dimension
- light signal



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

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

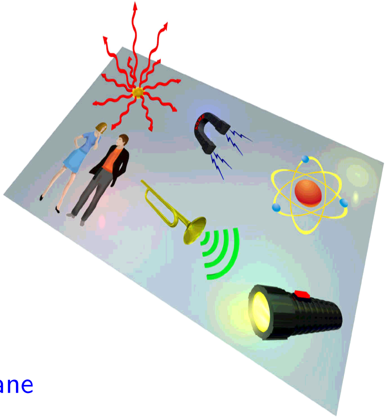
$\Rightarrow$ 3d: tower of Kaluza Klein particles with masses $M_n = n/R$

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

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

$\Leftrightarrow$ propagation in the internal space [30]

Our universe on a membrane



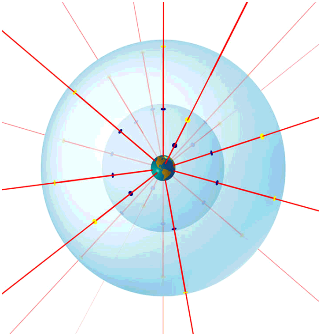
Two types of new dimensions:

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

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

Gravity modification at submillimeter distances

Newton's law: force decreases with area

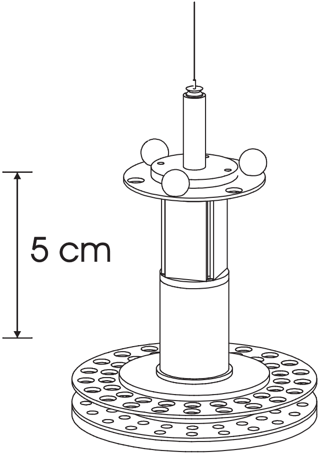


3d: force $\sim 1/r^2$

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

observable for $n=2$: $1/r^4$ with $r << .1$ mm [38]

Adelberger et al. '06



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

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

Experiment: Relativistic dark energy 70-75% of the observable universe

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

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

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 ?

Low scale gravity

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

total force = observed force $\times$ volume $\perp$

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

$$\Rightarrow \text{volume } R_\perp^n = 10^{32} \text{ in TeV}^{-1} \text{ units}$$

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

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

possible

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

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

  however for $< R_\perp$: gravity (3+n)d [35]

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

10^{30} times stronger than thought previously!

Low scale gravity

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

total force = observed force $\times$ volume $\perp$ [7]

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

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

Connect string theory to the real world:

What is the value of the string scale M_s ?

- arbitrary parameter : Planck mass $M_P \longrightarrow$ TeV

- physical motivations $\Rrightarrow$ favored energy regions:

- High : $\left\{ \begin{array}{ll} M_P^* \simeq 10^{18} \text{ GeV} & \text{Heterotic scale} \\ M_{\text{GUT}} \simeq 10^{16} \text{ GeV} & \text{Unification scale} \end{array} \right.$

- 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:

$M_s = g_H\, M_P \simeq 50\, M_{\rm GUT} \qquad g_H^2 \simeq \alpha_{\rm GUT} \simeq 1/25$ [43]

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

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

but loose predictivity

Heterotic string

gravity $\quad + \quad$ gauge $\quad$ kinetic terms [44]

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

simplified units: $2 = \pi = 1$

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

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

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

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

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

$M_p^2 \simeq \frac{1}{g_s^2} M_s^{2+n} R_\perp^n$ $g_s = \alpha$: weak string coupling [41]

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

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

$M_s \sim 1$ TeV $\Rightarrow R_\perp^n = 10^{32}\ l_s^n$ [68]

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

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

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

gravity + gauge kinetic terms

$$\int [d^{10}x]\,\frac{1}{g_s^2}M_s^8\,\mathcal{R}^{(10)} + \int [d^{p+1}x]\,\frac{1}{g_s}M_s^6\,\mathcal{F}_{MN}^2$$ [42]

Compactification in 4 dims $\Rightarrow$

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

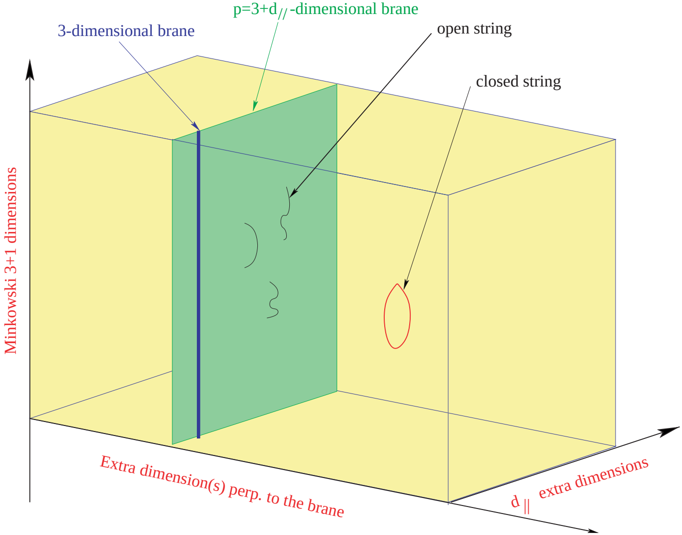
$\Rightarrow$

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

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

2 types of compact extra dimensions:

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



Origin of EW symmetry breaking?

possible answer: radiative breaking [27] I.A.-Benakli-Quiros '00

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

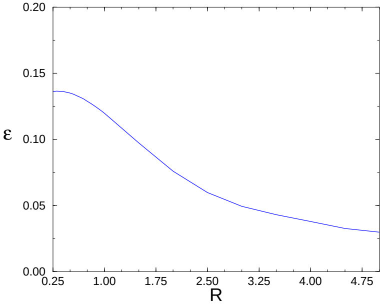
$\mu^2 = 0$ at tree but becomes < 0 at one loop non-susy vacuum

simplest case: one scalar doublet from the same brane

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

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

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



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

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

Higgs scalar = component of a higher dimensional gauge field

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

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

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

Accelerator signatures: 4 different scales

- Gravitational radiation in the bulk ⇛ missing energy

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

- Massive string vibrations ⇛ e.g. resonances in dijet distribution [53]

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

  higher spin excitations of quarks and gluons with strong interactions

  present LHC limits: $M_s \gtrsim 5$ TeV

- Large TeV dimensions ⇛ KK resonances of SM gauge bosons I.A. '90

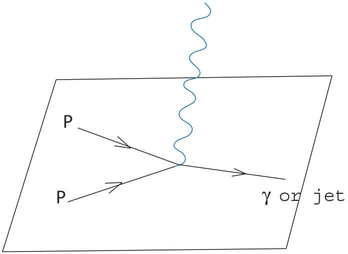
$$M_k^2 = M_0^2 + k^2/R^2 \ ; \ k = \pm 1, \pm 2, \ldots$$

  experimental limits: $R^{-1} \gtrsim 0.5 - 4$ TeV (UED - localized fermions) [55]

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

  masses suppressed by a loop factor from M_s [59]

Gravitational radiation in the bulk $\Rightarrow$ missing energy



Angular distribution $\Rightarrow$ spin of the graviton

present LHC bounds:

$M_* \gtrsim 3-5$ TeV [51]

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}

Supernova constraints

cooling due to graviton production e.g. $NN \to NN + \text{graviton}$

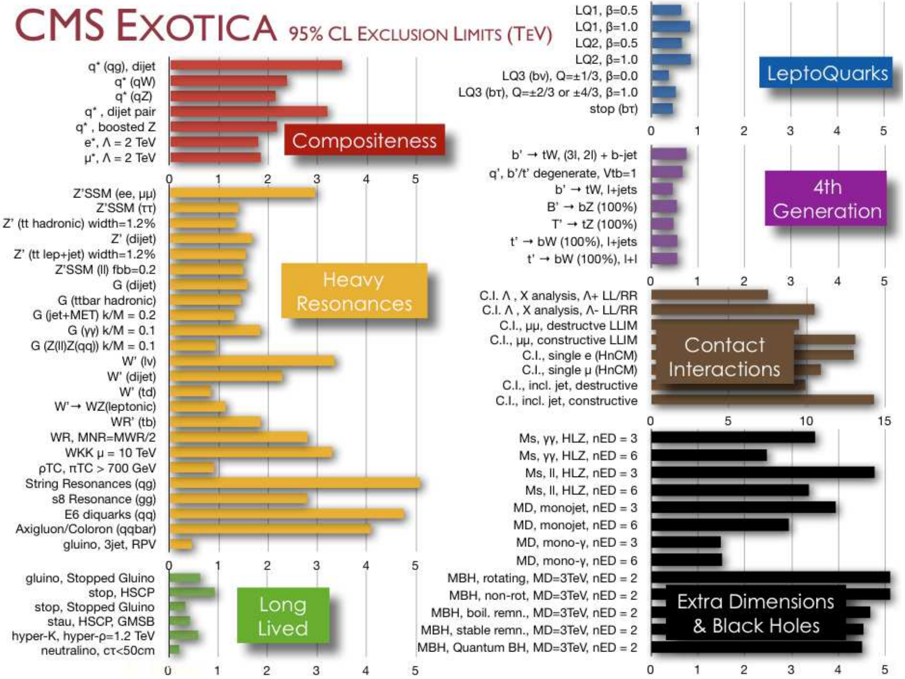
number of gravitons: $\sim (TR_\perp)^n$ $T >> R_\perp^{-1}$

~ 10 MeV

$\Rightarrow$ production rate: $P_{\rm gr} \sim \dfrac{1}{M_P^2}(TR_\perp)^n \sim \dfrac{T^n}{M_*^{(2+n)}}$

$P_{\rm gr} < P_\nu \;\Rightarrow\; M_*\big|_{n=2} \gtrsim 50\ \mathrm{TeV} \;\Rightarrow\; M_s \gtrsim 10\ \mathrm{TeV}$

CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)



Micro-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 : $M_j = M_s\sqrt{j} \Rightarrow$

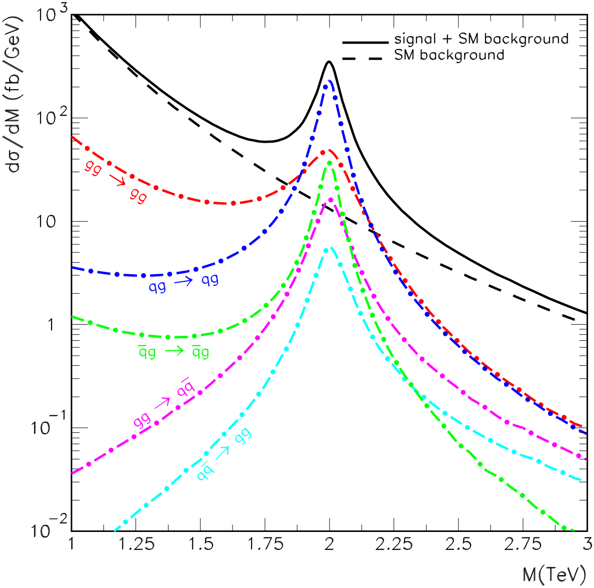
production of $j \sim 1/g_s^4 \sim 10^4$ string states before reach $M_{\rm BH}$ [48]

Universal deviation from Standard Model in jet distribution

$M_s = 2$ TeV

Width = 15-150 GeV

Anchordoqui-Goldberg-Lüst-Nawata-Taylor-Stieberger '08 [48] [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

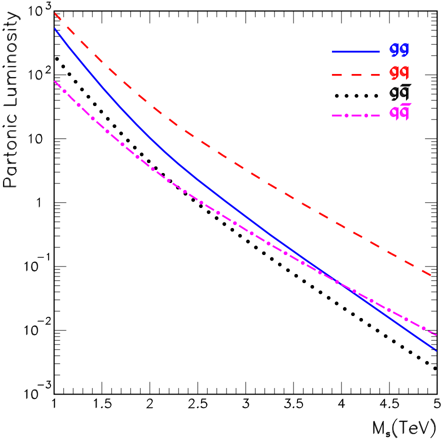
Universal sum over infinite exchange of string (Regge) excitations

Parton luminosities in pp above TeV

are dominated by gq, gg

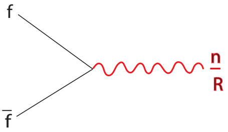
$\Rightarrow$ model independent

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



Localized fermions (on 3-brane intersections)

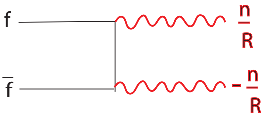
$\Rightarrow$ single production of KK modes I.A.-Benakli '94



- strong bounds indirect effects
- new resonances but at most $n = 1$

Otherwise KK momentum conservation

$\Rightarrow$ pair production of KK modes (universal dims)

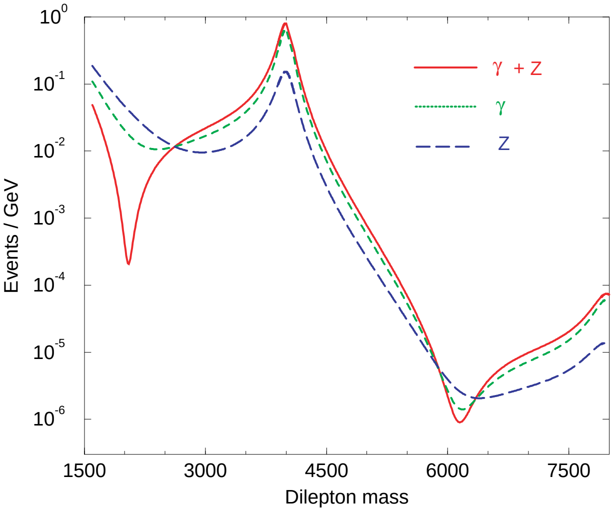


- weak bounds
- no resonances
- lightest KK stable $\Rightarrow$ dark matter candidate

Servant-Tait '02

$R^{-1} = 4$ TeV

I.A.-Benakli-Quiros '94, '99



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

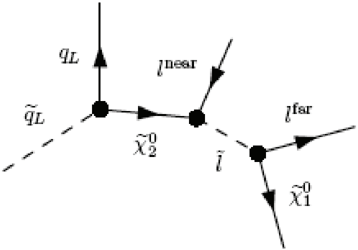
  spin determination important for distinguishing SUSY and UED [48]

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

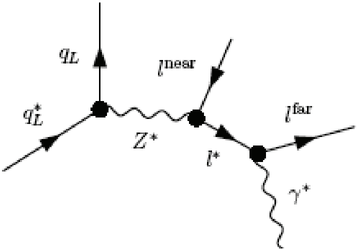
SUSY vs UED signals at LHC

Example: jet dilepton final state

SUSY



UED



Extra $U(1)$'s and anomaly induced terms

masses suppressed by a loop factor

usually associated to known global symmetries of the SM

(anomalous or not) such as (combinations of)

Baryon and Lepton number, or PQ symmetry

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

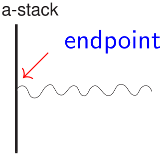
- 4d anomalous $U(1)$'s: $M_A \simeq g_A M_s$
- 4d non-anomalous $U(1)$'s: (but masses related to 6d anomalies)

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

or massless in the absence of such anomalies [62]

D-brane embedding of the Standard Model

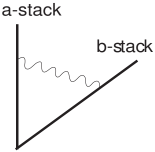
Generic spectrum: N coincident branes $\Rightarrow$ $U(N)$



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

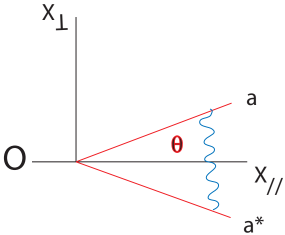
where closed strings change orientation

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

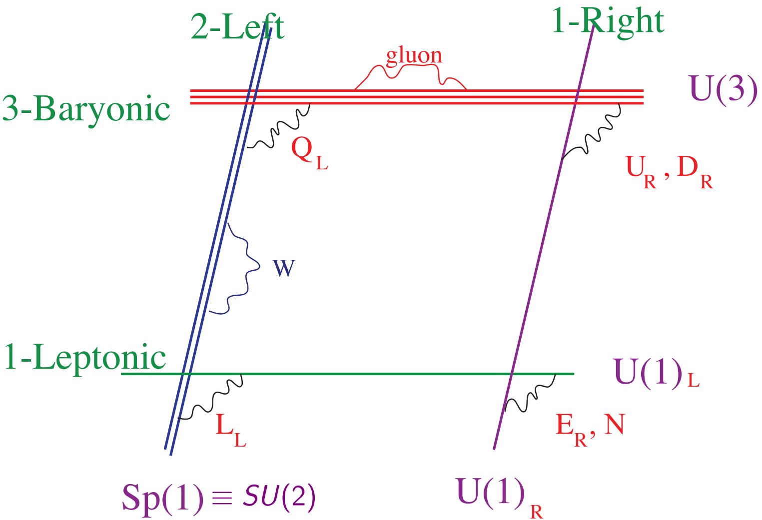
• strings stretched between two mirror stacks

Orientifold $\rightarrow$

$X_\perp \rightarrow -X_\perp$



$\Rightarrow$ antisymmetric or symmetric of $U(N_a)$



$U(1)^3 \Rightarrow$ 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: $\frac{\langle H\rangle^2}{M_s} LL$

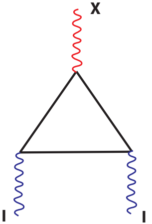
  $\sim$ GeV

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

  with possible leptophobic couplings leading to CDF-type Wjj events

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

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

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

but global symmetry remains in perturbation theory

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

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: $\dfrac{g_s v}{R_\perp^{n/2}} \nu_L \nu_R^0 \leftarrow$ 4d zero-mode

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

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

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

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

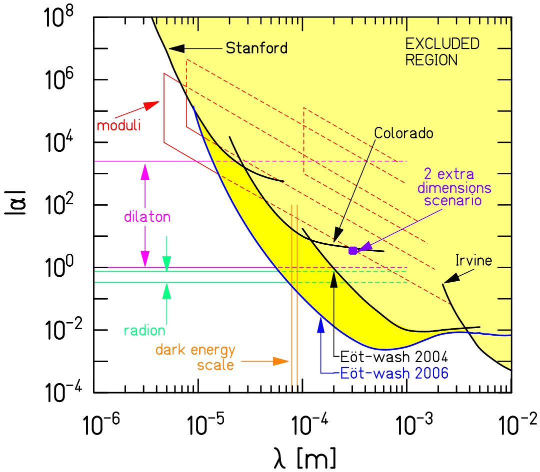
  can be experimentally tested for any number of extra dimensions

  - 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

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



Radion $\Rightarrow M_* \gtrsim 6$ TeV 95% CL Adelberger et al. '06 [75]

More general framework: large number of species

N particle species $\Rightarrow$ lower quantum gravity scale : $\quad M_*^2 = M_p^2/N$

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 [43]

   $N = R_\perp^n \, l_s^n$: 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

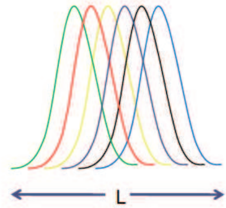
More general framework: large number of species

N particle species $\Rightarrow$ lower quantum gravity scale : $\quad M_*^2 = M_p^2/N$

Dvali '07, Dvali, Redi, Brustein, Veneziano, Gomez, Lüst '07-'10

derivation from: black hole evaporation or quantum information storage

Pixel of size L containing N species storing information:



localization energy $E \gtrsim N/L \rightarrow$

Schwarzschild radius $R_s = N/(LM_p^2)$

no collapse to a black hole : $L \gtrsim R_s \Rightarrow L \gtrsim \sqrt{N}/M_p = 1/M_*$

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

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

Aharony-Berkooz-Kutasov-Seiberg '98

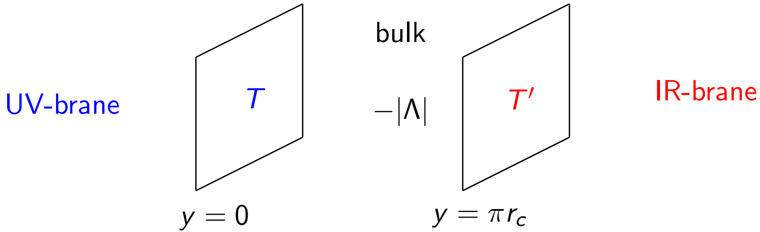
"cut" the space of the extra dimension $\Rightarrow$ gravity on the brane

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

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

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

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



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

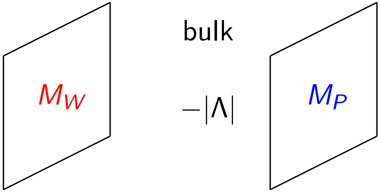
$m_n = c_n\, k\, e^{-2kr_c} \sim \mathrm{TeV} \quad c_n \simeq (n + 1/4)$ for large n

$\Rightarrow$ spin-2 TeV resonances in di-lepton or di-jet channels dilaton $\Phi = -\alpha|y|$ and flat metric $\Rightarrow$

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

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

SM-brane



Planck-brane

$y = 0$ $\qquad$ $y = r_c$

- 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

Radion stabilization

Cox-Gherghetta '12

Similar to RS using the dilaton as the Goldeberger-Wise scalar

add dilaton boundary potentials $\Rightarrow$

radion stabilization with the desired hierarchy

Radion phenomenology different from RS:

- mass spectrum: similar to the graviton KK modes

  with possible lower parametrically mass gap
- new radion couplings to SM fields besides to the trace of $T_{\mu\nu}$
- larger coupling to the radion 0-mode relative to KK excitations
- Higgs-radion mixing $\Rightarrow$

  branching fraction to $\gamma\gamma$ can be significantly enhanced

Conclusions

- Confirmation of the EWSB 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

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