Mass hierarchy and physics beyond the Standard Model

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School on the Future of Collider Physics

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- Mass hierarchy and 126 GeV Higgs
- Low energy SUSY
- Live with the hierarchy
- Extra $U(1)$'s
- Low scale strings and large extra dimensions

Standard Model of electroweak + strong forces

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

Very accurate description of physics at present energies   17 parameters

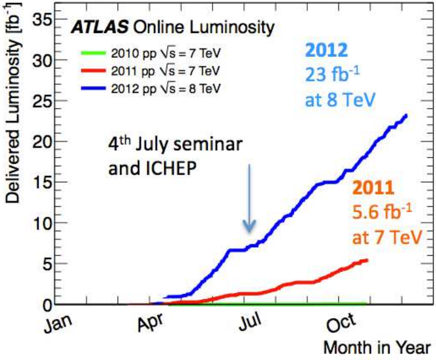
$$\mathcal{L}_{\rm SM} = -\frac{1}{2}\underset{\substack{\nearrow \\ \text{Forces}}}{\mathrm{tr}F_{\mu\nu}^2} + \bar{\psi}\not{D}\psi \underset{\substack{\uparrow \\ \text{Matter}}}{+} \bar{\psi}YH\psi - |DH|^2 \underset{\substack{\uparrow \\ \text{Higgs}}}{-} V(H)$$

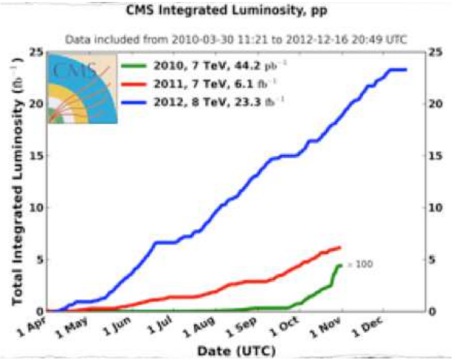
minimal Higgs sector: $V(H) = -\mu^2|H|^2 + \lambda\left(|H|^2\right)^2$

Its discovery was one of the main goals of LHC

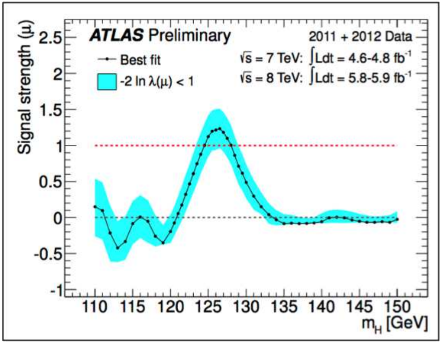
Excellent LHC performance

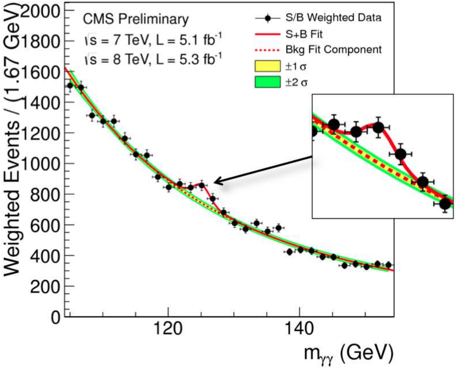
Number of events = Cross section × Luminosity



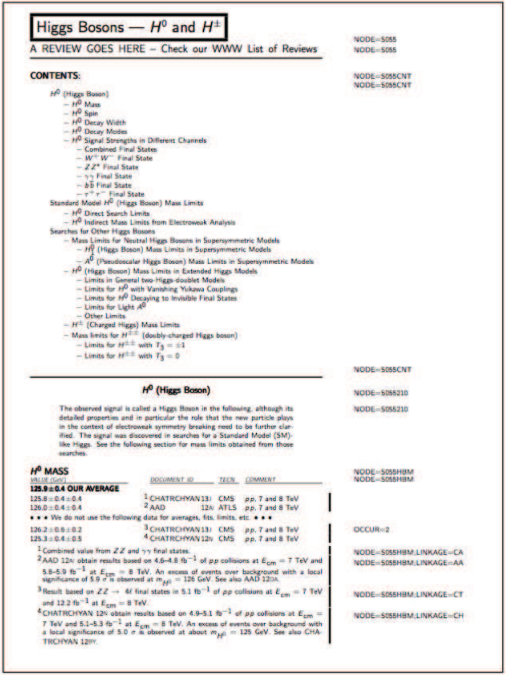


Higgs boson discovery





$m_H = 125.5 \pm 0.2\,(\mathrm{stat.}) \pm 0.5\,(\mathrm{syst.})$ $m_H = 125.7 \pm 0.3 \pm 0.3$ GeV



Higgs Bosons — H^0 and $H^\pm$

A REVIEW GOES HERE – Check our WWW List of Reviews

NODE=S055
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CONTENTS:

NODE=S055CNT
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H^0 (Higgs Boson)

NODE=S055210

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.

NODE=S055210

H^0 MASS

NODE=S055HBM
NODE=S055HBM

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

OCCUR=2

[1] Combined value from ZZ and $\gamma\gamma$ final states.

NODE=S055HBM;LINKAGE=CA

[2] AAD 12AI obtain results based on 4.6–4.8 fb^{-1} of pp collisions at $E_{\text{cm}} = 7$ TeV and 5.8–5.9 fb^{-1} at $E_{\text{cm}} = 8$ TeV. An excess of events over background with a local significance of 5.9 σ is observed at $m_{H^0} = 126$ GeV. See also AAD 12DA.

NODE=S055HBM;LINKAGE=AA

[3] Result based on $ZZ \to 4\ell$ final states in 5.1 fb^{-1} of pp collisions at $E_{\text{cm}} = 7$ TeV and 12.2 fb^{-1} at $E_{\text{cm}} = 8$ TeV.

NODE=S055HBM;LINKAGE=CT

[4] CHATRCHYAN 12N obtain results based on 4.9–5.1 fb^{-1} of pp collisions at $E_{\text{cm}} =$ 7 TeV and 5.1–5.3 fb^{-1} at $E_{\text{cm}} = 8$ TeV. An excess of events over background with a local significance of 5.0 σ is observed at about $m_{H^0} = 125$ GeV. See also CHATRCHYAN 12BY.

NODE=S055HBM;LINKAGE=CH

Entrance of the Higgs Boson
in the Particle Data Group
(PDG) 2013 !

H^0

Beyond the Standard Model 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

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?

Standard picture: low energy supersymmetry

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

cancel large quantum corrections to the Higgs mass

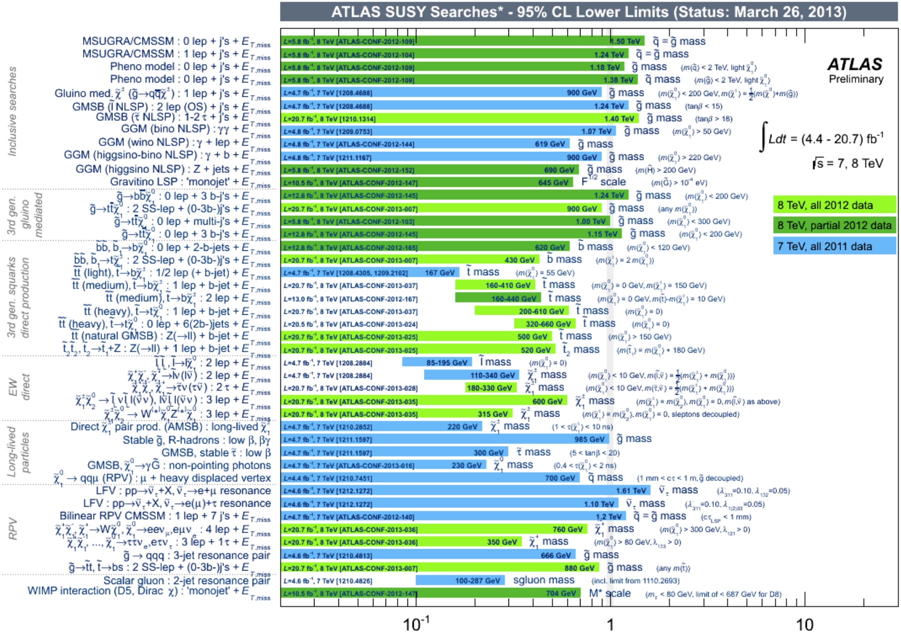
Advantages:

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

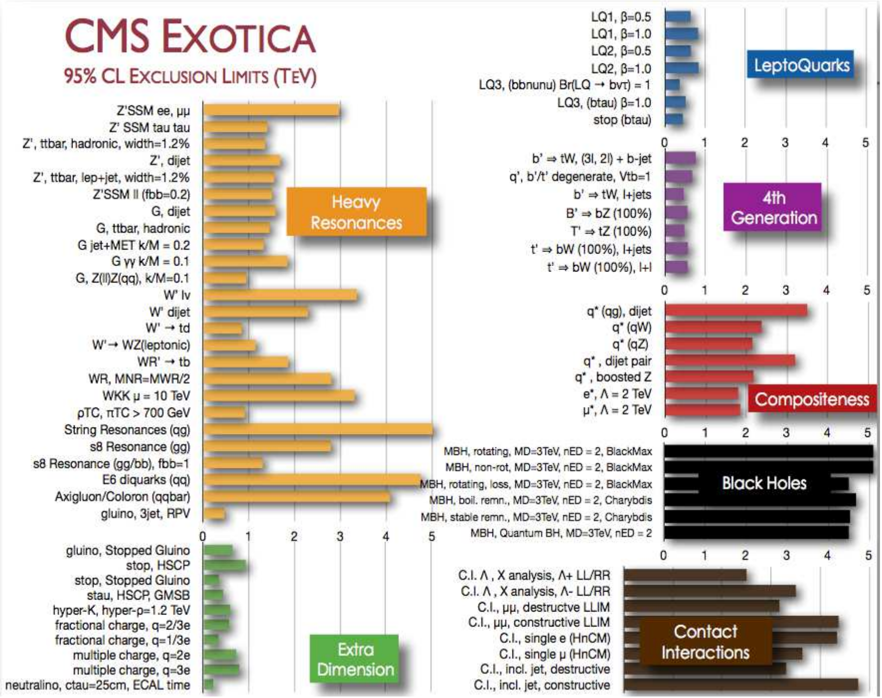
Problems:

- 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)
Heavy Resonances
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
0
1
2
3
4
5
Extra Dimension
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
LeptoQuarks
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)
0
1
2
3
4
5
4th Generation
b' ⇒ tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' ⇒ tW, l+jets
B' ⇒ bZ (100%)
T' ⇒ tZ (100%)
t' ⇒ bW (100%), l+jets
t' ⇒ bW (100%), l+l
0
1
2
3
4
5
Compositeness
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
0
1
2
3
4
5
Black Holes
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
0
1
2
3
4
5
Contact Interactions
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive

Remarks on the value of the Higgs mass ~ 126 GeV

- consistent with expectation from precision tests of the SM
- favors perturbative physics quartic coupling $\lambda = m_H^2/v^2 \simeq 1/8$

Window to new physics

- compatible with supersymmetry

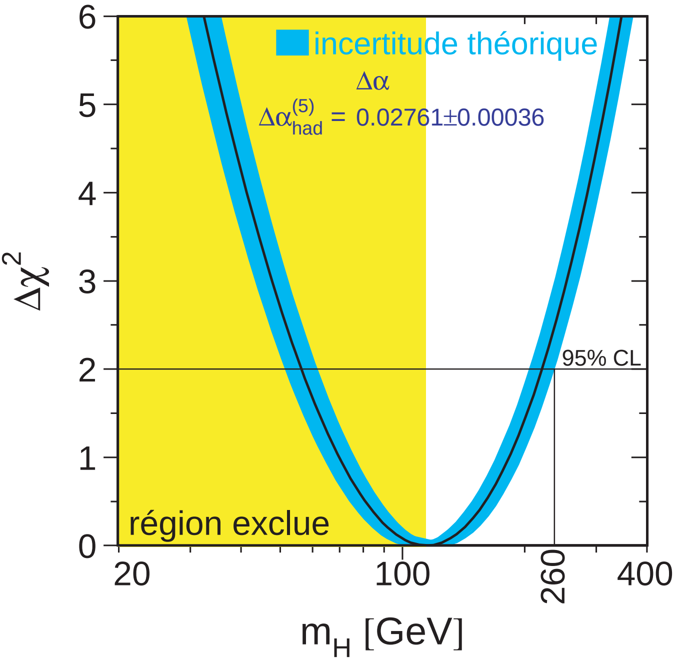
  but appears fine-tuned in its minimal version [12]

  early to draw a general conclusion before LHC13/14

  e.g. an extra singlet or split families can alleviate the fine tuning [13]
- very important to measure its properties and couplings [17]

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

RG evolution: $m_2^2 = \; m_2^2(M_{\rm GUT}) - \dfrac{3\lambda_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln\dfrac{M_{\rm GUT}}{m_{\tilde{t}}} + \cdots$ [31]

$$\sim m_2^2(M_{\rm GUT}) - \mathcal{O}(1) m_{\tilde{t}}^2 + \cdots$$ [10]

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_1 : corresponding soft breaking term spurion $S \equiv m_S \, \theta^2$

Physical consequences of MSSM_5: Scalar potential

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

- $\eta_{1,2} \Rightarrow$ quartic terms along the D-flat direction $|h_1| = |h_2|$
- potential stability $\Rightarrow \eta_2 \geq 4|\eta_1|$

requiring η-corrections to be smaller than MSSM mass matrix elements $\Rightarrow$

only η_2 can change the tree-level bound $m_h \leq m_Z$ but marginally

Relevance of dim-6 operators

Relaxing the condition on potential positivity: guaranteed by dim-6 ops

only one dim-6 along the D-flat direction induced by dim-5: $\propto \eta_1^2$

$$W = \eta_1 (H_1 H_2)^2 \longrightarrow V = \left|\frac{\partial W}{\partial H_i}\right|^2 \sim \eta_1^2 \, |H_1 H_2|^2 \left(|H_1|^2 + |H_2|^2\right)$$

- tree-level mass can increase significantly
- bigger parameter space for LSP being dark matter

Bernal-Blum-Nir-Losada '09

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 $\mathrm{SU}\not{\mathrm{S}}\mathrm{Y}$) $\Rightarrow$

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

constant receiving contributions from several operators

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

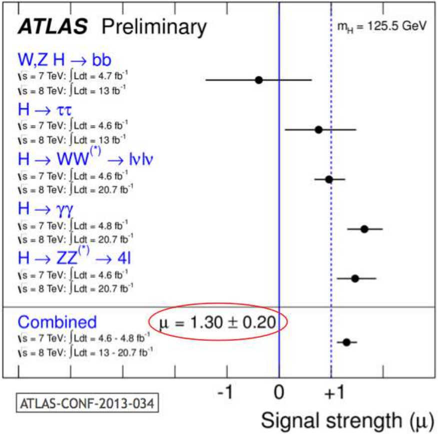
$m_S = 1$ TeV, $M = 10$ TeV, $f_0 \sim 1 - 2.5$ for each operator

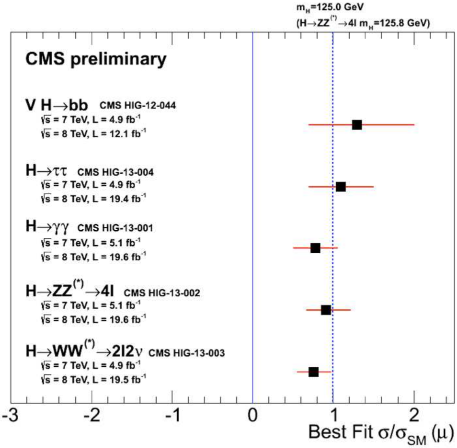
$\Rightarrow m_h \simeq 103 - 119$ GeV

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

possible resolution of the MSSM fine-tuning problem [10]

Couplings of the new boson vs SM



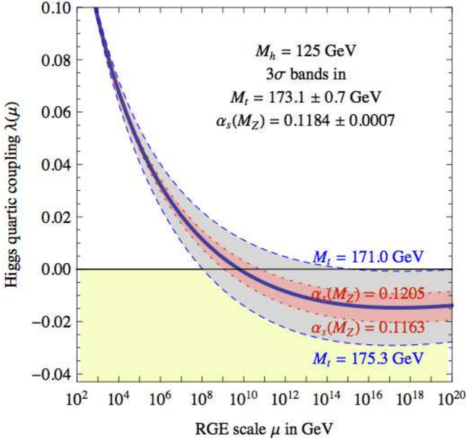


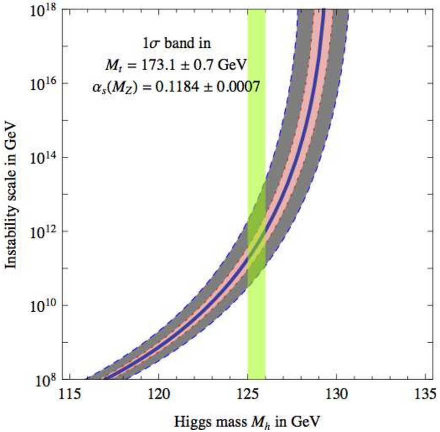
exclusion : spin 2 and pseudoscalar at 95% CL

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

Can the SM be valid at high energies?

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





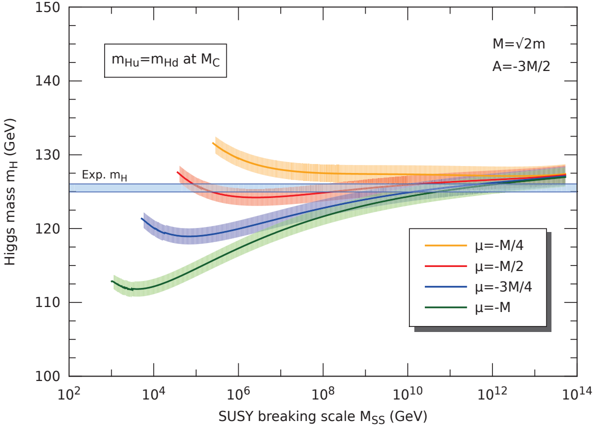
Instability of the SM Higgs potential ⇒ metastability of the EW vacuum

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

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

$\lambda = 0$ 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 ⇒ 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 ⇒ 'moderate' split

  $m_S \sim$ few - thousands TeV

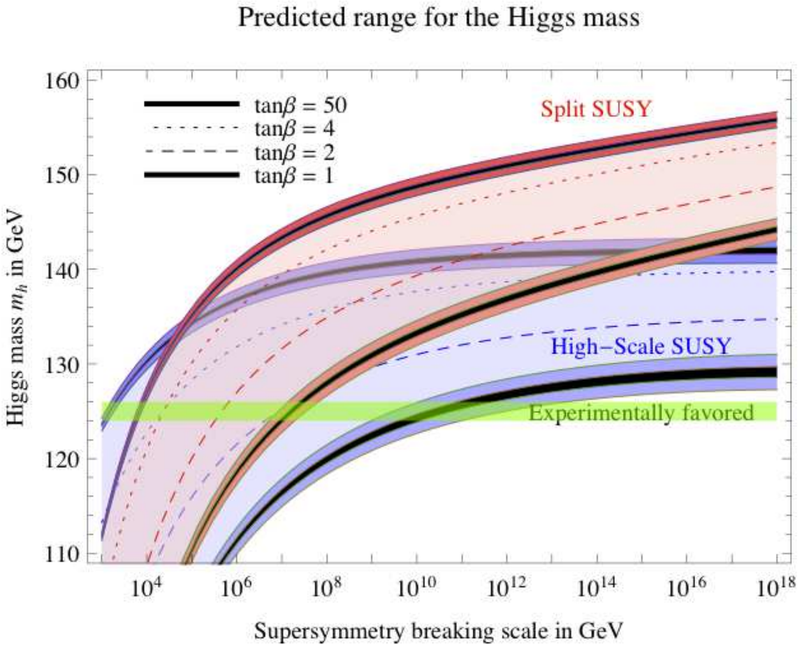
  gauginos: a loop factor lighter than scalars ($\sim m_{3/2}$)
- natural string framework: intersecting (or magnetized) branes

  IA-Dimopoulos '04

  D-brane stacks are supersymmetric with massless gauginos

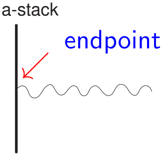
  intersections have chiral fermions with broken SUSY & massive scalars

Giudice-Strumia '11



D-brane embedding of the Standard Model

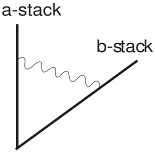
Generic spectrum: N coincident branes $\Rightarrow$ $U(N)$



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

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

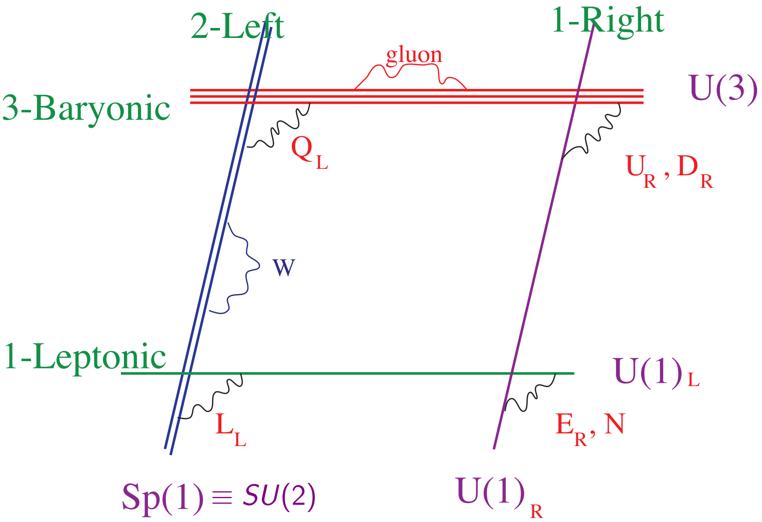
Anchordoqui-IA-Goldberg-Huang-Lüst-Taylor-Vlcek '12

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)

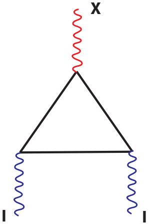
  but broken at TeV by a scalar VEV with the quantum numbers of N_R
- L-violation from higher-dim operators suppressed by the string scale
- $U(3)$ unification, Y combination $\Rightarrow$ 2 parameters: 1 coupling + $m_{Z''}$
- perturbativity $\Rightarrow 0.5 \lesssim g_{U(1)_R} \lesssim 1$ [26]
- interesting LHC phenomenology and cosmology [27]

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



$U(1)^3 \Rightarrow$ hypercharge + B, L [46]

Green-Schwarz anomaly cancellation



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

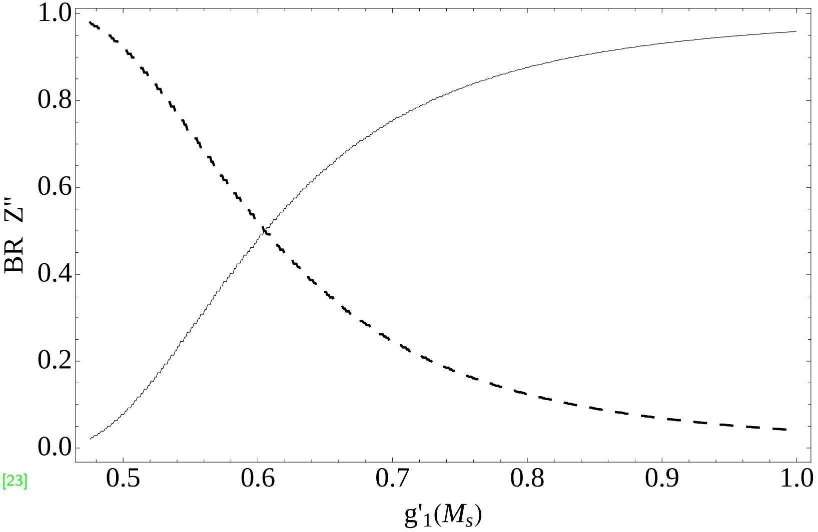
$$-\frac{1}{4g_I^2}\,F_I^2 - \frac{1}{2}\,(d\theta + m_A A)^2 + \frac{\theta}{m_A}\,k_I^A\,\mathrm{Tr}\,F_I \wedge F_I$$

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 $\quad d\theta = *dB_2$ [23]



$U(1)_R$

$B - L$

[23]

- Rotation of $U(1)$'s from the string to low energy basis Z, Z', Z'':

  completely fixed in terms of the couplings

  - Decoupling of anomalous $Z' \simeq B$
  - Z'' linear combination of $B - L$ and $U(1)_R$

- Recent cosmological observations indicate extra relativistic component

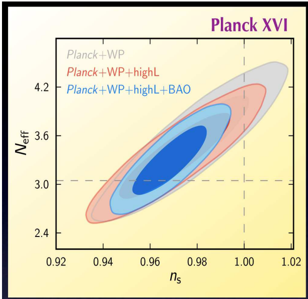
  dark radiation parametrized by an effective ν-number close to 4 *

  → use the 3 ν_R's interacting with SM fermions via Z''

  data: their decoupling during the quark-hadron transition

  $\Rightarrow 3.5 \lesssim M_{Z''} \lesssim 7$ TeV (within LHC14 discovery potential)

  * before Planck results



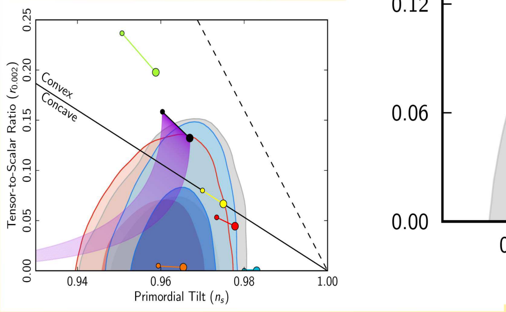


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

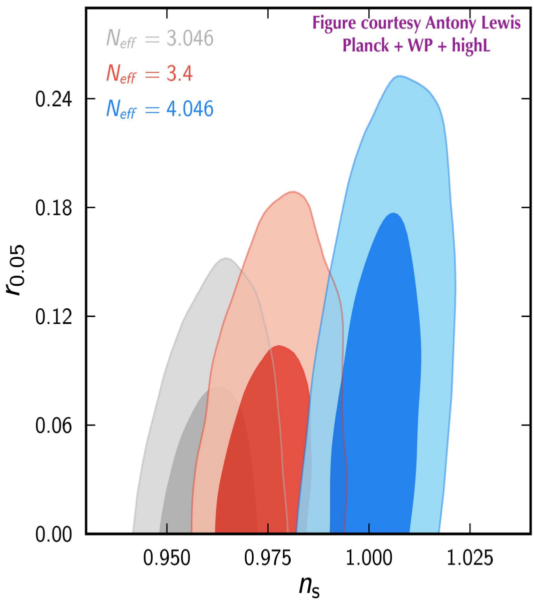


Figure courtesy Antony Lewis
Planck + WP + highL

Stability analysis in (non-susy) SM^{++} AAGHLTV '12

Scalar potential:

$$V\left(H, H''\right) = \mu^2 \left|H\right|^2 + {\mu'}^2 \left|H''\right|^2 + \lambda_1 \left|H\right|^4 + \lambda_2 \left|H''\right|^4 + \lambda_3 \left|H\right|^2 \left|H''\right|^2$$

5 parameters $\Rightarrow v, m_h, v'', m_{h''}$ + a scalar mixing angle α

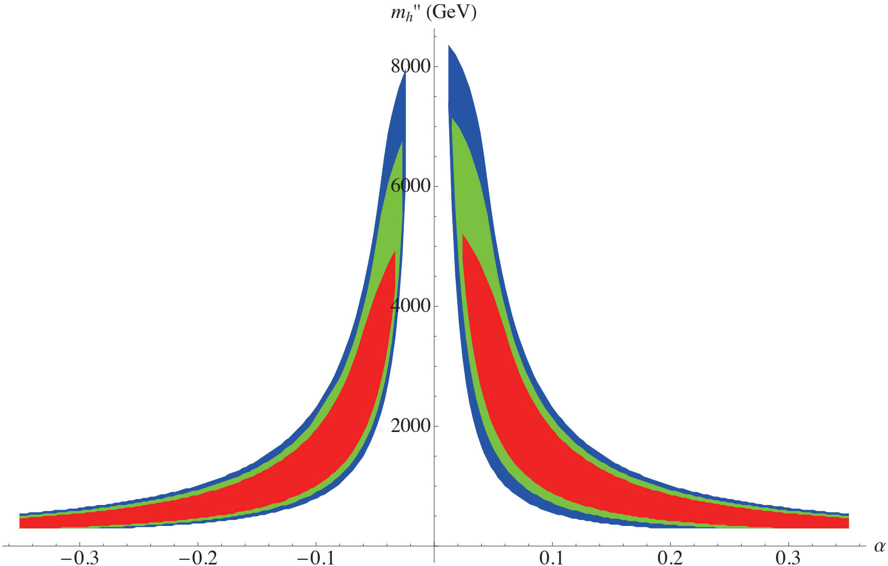
$\Rightarrow$ 3 free parameters : $m_{h''}, \alpha, v'' \leftrightarrow M_{Z''}$

Stability conditions: $\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_1\lambda_2 > \frac{1}{4}\lambda_3^2$

RGE analysis up to $M_s \Rightarrow$ stability is possible in SM^{++}

for $0.02 \lesssim |\alpha| \lesssim 0.35$ and $500\ \mathrm{GeV} \lesssim m_{h''} \lesssim 5\ \mathrm{TeV}$

$M_{Z''} = 4.5$ TeV; $M_s = 10^{14}, 10^{16}, 10^{19}$ GeV



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

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

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

$M_s \sim 1$ TeV $\Rightarrow$ volume $R_\perp^n = 10^{32}\, l_s^n$ [48] ($R_\perp \sim .1 - 10^{-13}$ mm for $n = 2 - 6$)

- spectacular model independent predictions

- radical change of high energy physics at the TeV scale

Moreover no little hierarchy problem:

radiative electroweak symmetry breaking with no logs

$\Lambda \sim$ a few TeV and $m_H^2 =$ a loop factor $\times\, \Lambda^2$ [12] [35]

But unification has to be probably dropped

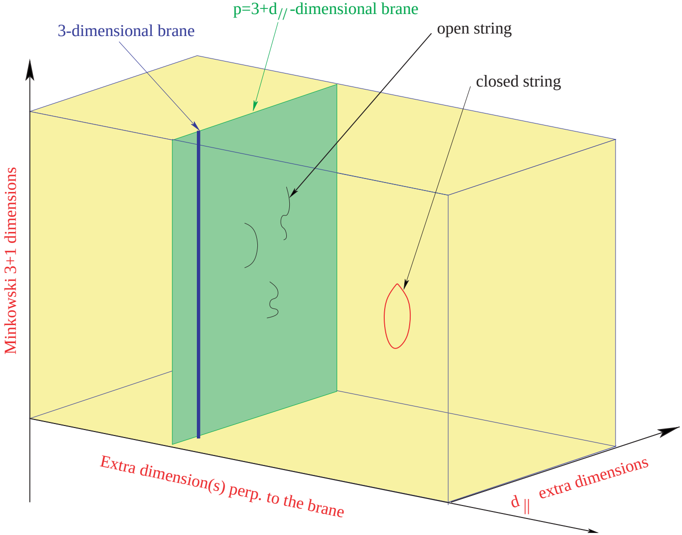
New Dark Matter candidates e.g. in the extra dims

Braneworld

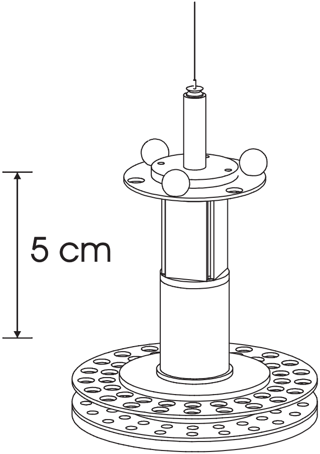
I.A.-Arkani-Hamed-Dimopoulos-Dvali '98

2 types of compact extra dimensions:

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



Adelberger et al. '06



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

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

Framework of type I string theory $\Rightarrow$ D-brane world

- 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

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

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

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

distances $< R_\perp$: gravity $(4+n)$-dim → strong at 10^{-16} cm [31]

Origin of EW symmetry breaking?

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

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

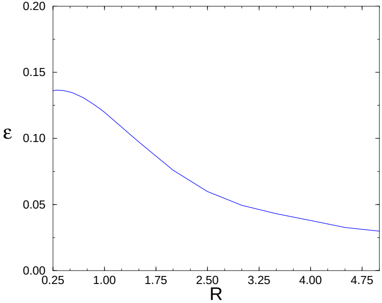
$\mu^2 = 0$ at tree but becomes < 0 at one loop non-susy vacuum

simplest case: one 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

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



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

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

Higgs scalar = component of a higher dimensional gauge field

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

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

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

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 [40]

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

  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

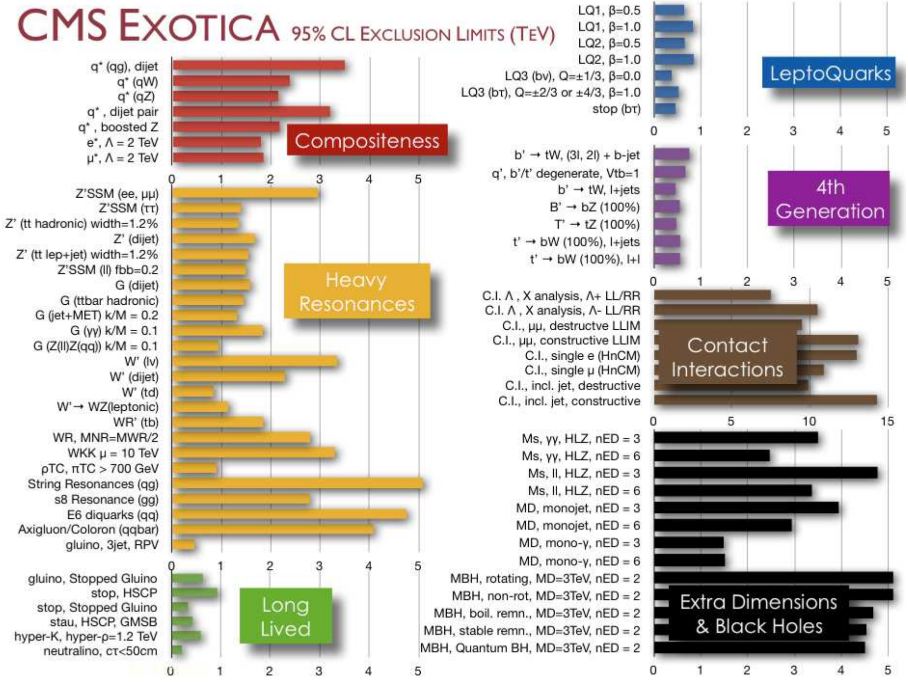
  $$M_k^2 = M_0^2 + k^2/R^2 \;\; ; \;\; k = \pm 1, \pm 2, \ldots$$

  experimental limits: $R^{-1} \gtrsim 0.5 - 4$ TeV (UED - localized fermions) [42]

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

  masses suppressed by a loop factor from M_s [46]

CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)



Micro-black hole production?

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

Horowitz-Polchinski '96, Meade-Randall '07

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

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

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

Comparison with Regge excitations : $M_j = M_s\sqrt{j} \;\Rightarrow$

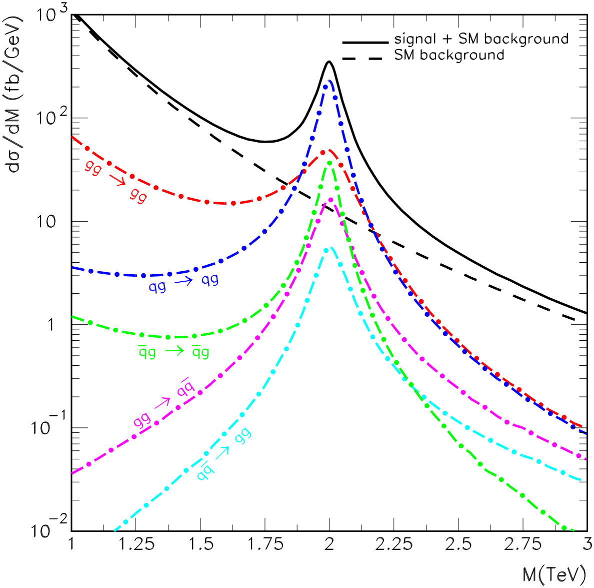
production of $j \sim 1/g_s^4 \sim 10^4$ string states before reach M_{BH}

Universal deviation from Standard Model in jet distribution

$M_s = 2$ TeV

Width = 15-150 GeV

Anchordoqui-Goldberg-Lüst-Nawata-Taylor-Stieberger '08 [37]



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

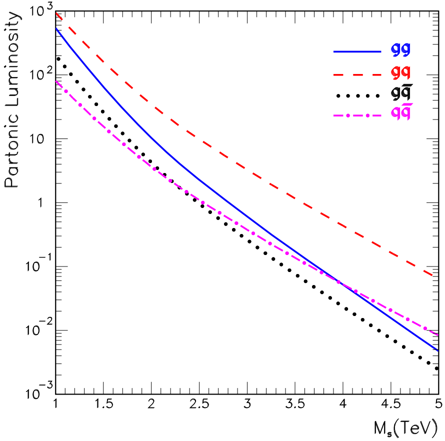
Universal sum over infinite exchange of string (Regge) excitations [37]

Parton luminosities in pp above TeV

are dominated by *gq*, *gg*

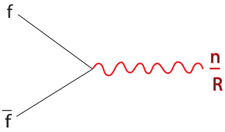
⇒ model independent

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



Localized fermions (on 3-brane intersections)

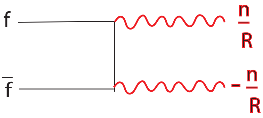
⇒ single production of KK modes I.A.-Benakli '94



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

Otherwise KK momentum conservation [44]

⇒ pair production of KK modes (universal dims)

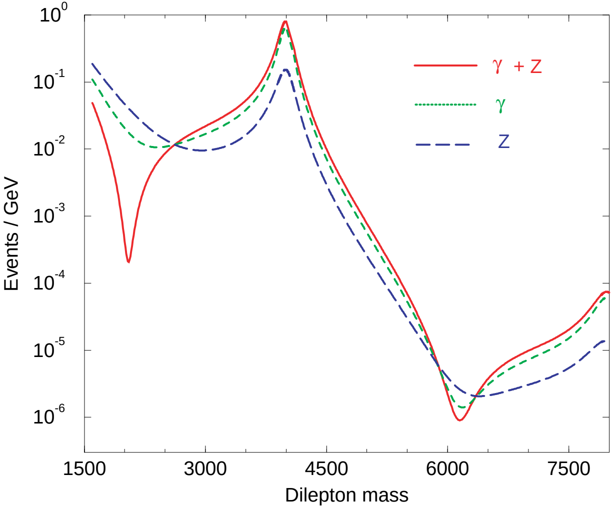


- weak bounds
- no resonances
- lightest KK stable ⇒ dark matter candidate

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

  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

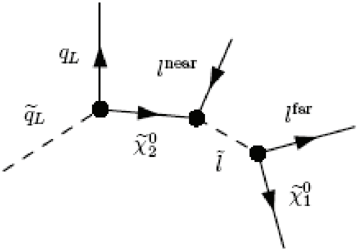
  spin determination important for distinguishing SUSY and UED [37]

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

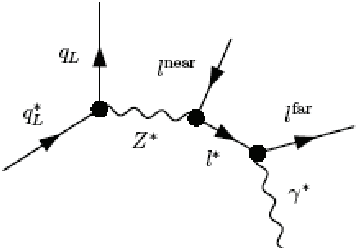
SUSY vs UED signals at LHC

Example: jet dilepton final state

SUSY



UED



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

masses suppressed by a loop factor

usually associated to known global symmetries of the SM

(anomalous or not) such as (combinations of)

Baryon and Lepton number, or PQ symmetry

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

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

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

or massless in the absence of such anomalies [24]

TeV string scale

Anchordoqui-IA-Goldberg-Huang-Lüst-Taylor '11

- 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 $\Rrightarrow \frac{1}{M_s} LLHH \rightarrow$ Majorana mass: $\frac{\langle H \rangle^2}{M_s} LL$

  $\nwarrow \sim$ 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 $Z'' \simeq B - L$

More general framework: large number of species

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

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

derivation from: black hole evaporation or quantum information storage

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

2 ways to realize it lowering the string scale

1. Large extra dimensions SM on D-branes [31]

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

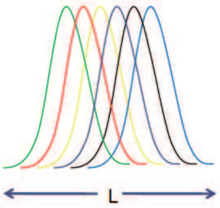
More general framework: large number of species

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

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

derivation from: black hole evaporation or quantum information storage

Pixel of size L containing N species storing information:



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

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

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

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

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

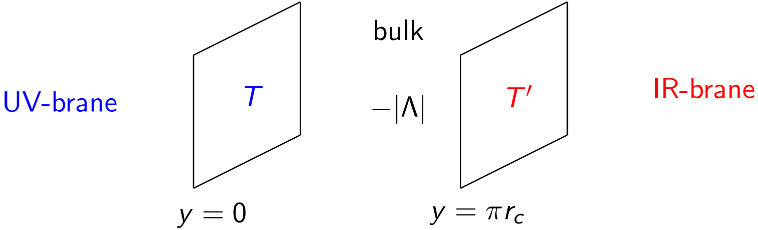
$$S_{bulk} = \int d^4x \int_0^{r_c} dy \sqrt{-g}\, e^{-\Phi} \left(M_5^3 R + M_5^3 (\nabla\Phi)^2 - \Lambda\right)$$

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

Tuning conditions: $T_{vis} = -T_{hid} \leftrightarrow \Lambda < 0$ [52]

Constant dilaton and AdS metric : Randal Sundrum model

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



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

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

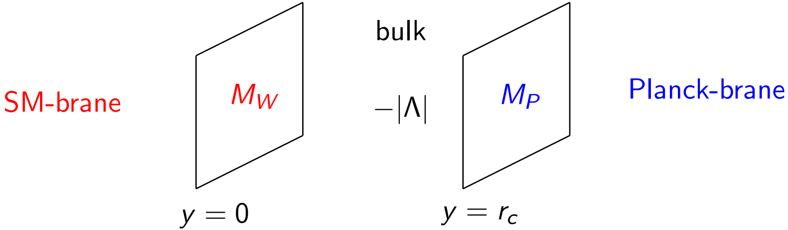
$\Rightarrow$ spin-2 TeV resonances in di-lepton or di-jet channels

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

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

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

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



bulk

SM-brane

M_W

$-|\Lambda|$

M_P

Planck-brane

$y = 0$

$y = r_c$

- 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

LST KK graviton phenomenology

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

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

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

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

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

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

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

  $\Rightarrow$ distinct experimental signals

Conclusions

- Higgs discovery 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

European Strategy
Update

There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate.
Europe looks forward to a proposal from Japan to discuss a possible participation.