Mass hierarchies in string theory and experimental predictions

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- High string scale, SUSY and 125 GeV Higgs
- Low scale strings
- Extra $U(1)$'s

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

Standard picture: low energy supersymmetry

Advantages:

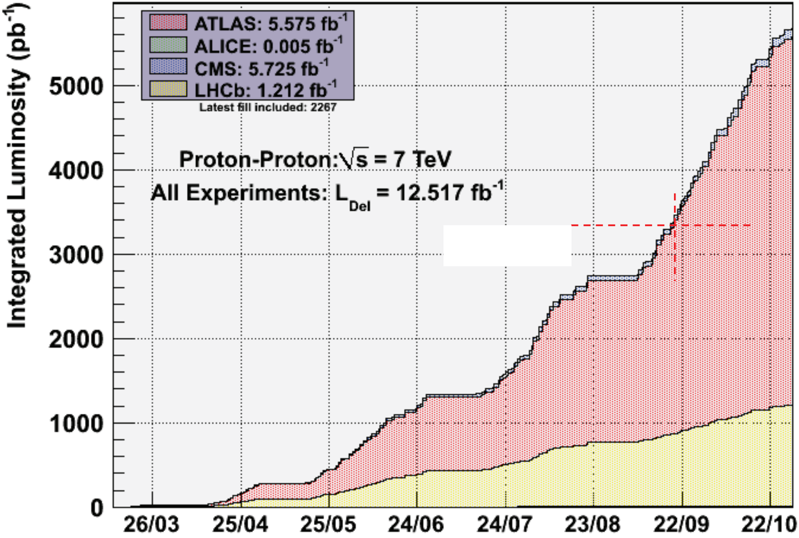
- natural elementary scalars
- gauge coupling unification
- LSP: natural dark matter candidate
- radiative EWSB

Problems:

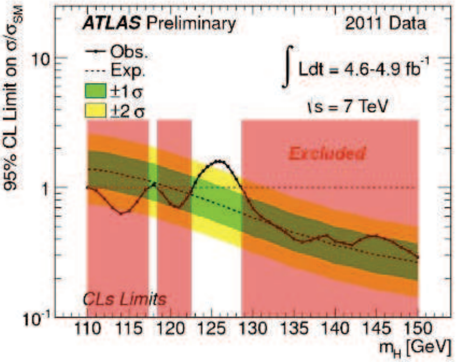
- too many parameters: soft breaking terms
- MSSM : already a % - ‰ fine-tuning 'little' hierarchy problem

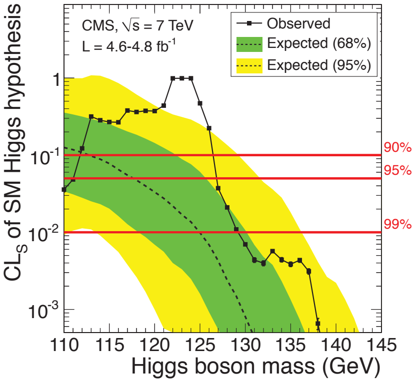
Natural framework: Heterotic string (or high-scale M/F) theory

LHC Luminosity 2011



Higgs search





$117.5 < m_H < 118.5$

or

$122.5 < m_H < 129$

$114.5 < m_H < 127.5$

SUSY / invisibles: summary

- Analysis of **2011** data still in flow
  - Several analyses with full 5 fb^{-1}, more on the way
- Lower limits* of:
  - **squark ~ 1400 GeV**
  - **gluino ~ 900 GeV**
  - **sbottom ~ 400 GeV**
  - **[stop ~ 300 GeV]****
  - **[gauginos ~ 200-300 GeV]****

* indicative
& for particular scenarios

Direct production
Particular decays

- Also: taus, photons, monojets, disappearing tracks, … + E_T^{miss}
- Preparations for **2012, 8 TeV** in full swing

2012 performance estimate

15-19 fb

- 4 TeV, 50 ns, 1380 bunches, 1.6×10^{11}, 2.5 μm
  150 days of proton physics (assuming similar efficiencies to 2011)

	Beta* [cm]	Collimators	Peak Lumi [$cm^{-2}s^{-1}$]	Int. Lumi [fb^{-1}]	Pile-up	Increase in peak
50ns	90	Intermediate	5.1e33	12.1 – 14.5	26	
	70	Tight	6.2e33	14.7 – 17.6	31	+22%
	60	Tight	6.8e33	16.2 – 19.3	35	+10%
25ns						
	80	Tight	3.8e33	8.3	10	

reconfirms the decision for 50ns

some conclusions

Higgs-like excess in the light mass region :

- consistent with expectation from precision tests of the SM
- favors perturbative physics (technicolor is falsified again)

If its mass is confirmed around 125 GeV :

- supersymmetry becomes ‘severely’ fine-tuned, in its minimal version
- but too early to have a general conclusion before LHC13/14

  for instance, adding a singlet can remediate the fine tuning to $\Delta < 10$

  Pinner-Ruderman-Hall ’11; Ghilencea’s talk

- very important to measure Higgs 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

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

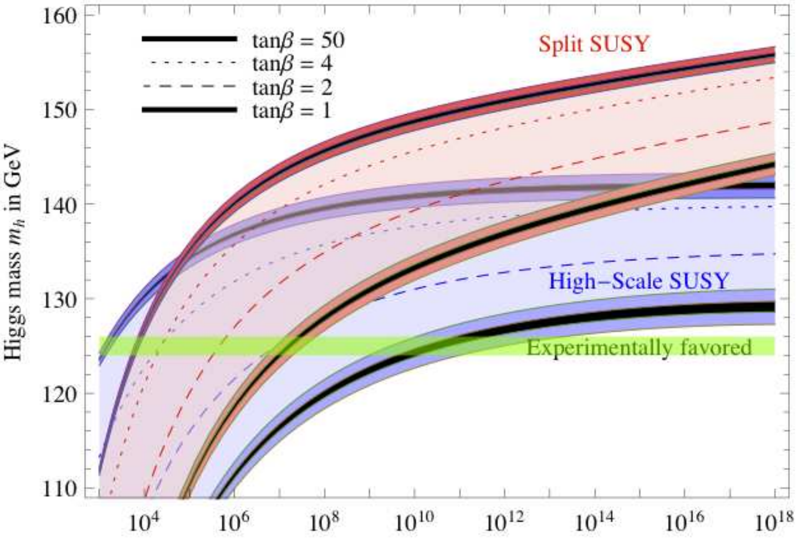
  IA-Dimopoulos '04

  D-brane stacks are supersymmetric with massless gauginos

  intersections have chiral fermions with broken SUSY & massive scalars

Giudice-Strumia '11

Predicted range for the Higgs mass



Supersymmetry breaking scale in 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

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

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

But unification has to be probably dropped

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

Framework of 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 $\Rightarrow$ $R_\parallel \simeq l_{\mathrm{string}}$; $R_\perp$ 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 : extra-large $R_\perp$

$M_s \sim 1$ TeV $\Rightarrow$ $R_\perp^n = 10^{32}\, l_s^n$ [23]

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

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

Origin of EW symmetry breaking?

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

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

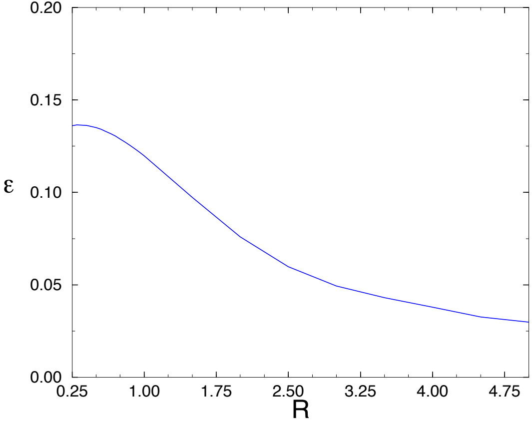
$\mu^2 = 0$ at tree but becomes < 0 at one loop non-susy vacuum

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

Quartic coupling $\Rrightarrow$ mass prediction:

- tree level : $M_H = M_Z$

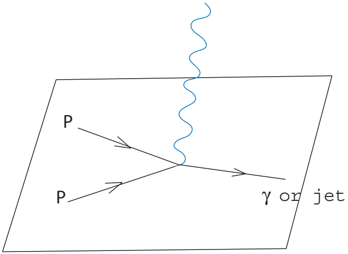
- low-energy SM radiative corrections (from top quark) : $M_H \sim 120$ GeV

Casas-Espinosa-Quiros-Riotto, Carena-Espinosa-Quiros-Wagner '95

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

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

Gravitational radiation in the bulk ⇒ missing energy



Angular distribution ⇒ spin of the graviton

present LHC bounds:

$M_* \gtrsim 2 - 3.5$ TeV

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

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

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 $M_{\rm BH}$

Other accelerator signatures: 3 different scales

- string physics

  Massive string vibrations ⇒ e.g. resonances in dijet distribution

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

  higher spin excitations of quarks and gluons with strong interactions

- Large TeV dimensions seen by SM gauge interactions

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

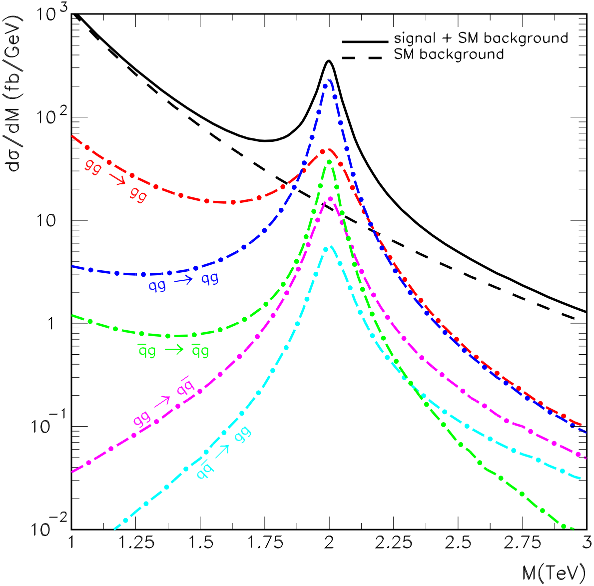
  $$M_k^2 = M_0^2 + \frac{k^2}{R^2} \;;\; k = \pm 1, \pm 2, \ldots \quad R = V_\parallel^{1/d_\parallel} \quad ; \quad g^2 = 1/(V_\parallel M_s^{d_\parallel})$$

  experimental limits: $R^{-1} \gtrsim 0.5 - 4$ TeV (UED - localized fermios)

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

  masses suppressed by a loop factor from M_s [19]

Universal deviation from Standard Model in dijet distribution



$M_s = 2$ TeV

Width = 15-150 GeV

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

present LHC limits: $M_s \gtrsim 4$ TeV

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

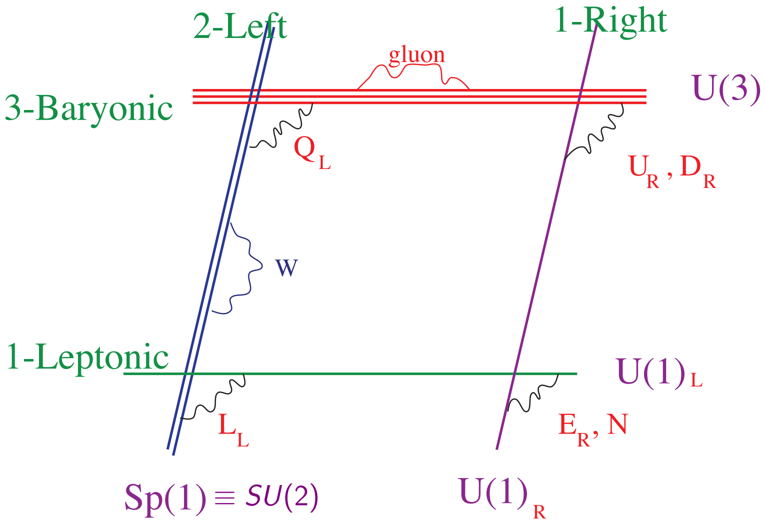
Two kinds of massive $U(1)$'s: I.A.-Kiritsis-Rizos '02

- 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

Standard Model on D-branes



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

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 $\Rrightarrow \frac{1}{M_s} LLHH \longrightarrow$ 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 $Z'' \simeq B - L$

High string scale

AAGHLT+Vlcek in preparation

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

  but broken at TeV by a Higgs VEV with the quantum numbers of N_R
- L-violation from higher-dim operators suppressed by the string scale
- present LHC limits: $m_{Z''} \gtrsim 2.5$ TeV [11] [28]

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 [11]

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

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

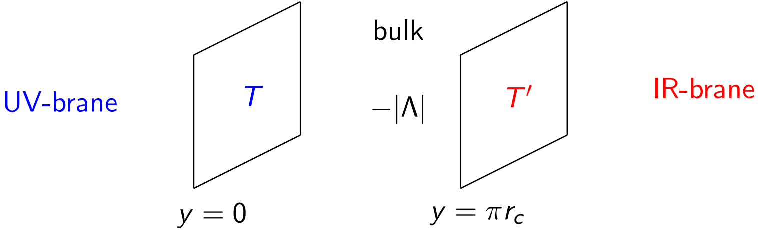
"cut" the space of the extra dimension $\Rightarrow$ gravity on the brane

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

Tuning conditions: $T_{vis} = -T_{hid} \leftrightarrow \Lambda < 0$ [26]

Randal Sundrum models

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



bulk

UV-brane $\quad T \quad$ $-|\Lambda|$ $\quad T' \quad$ IR-brane

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

- 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

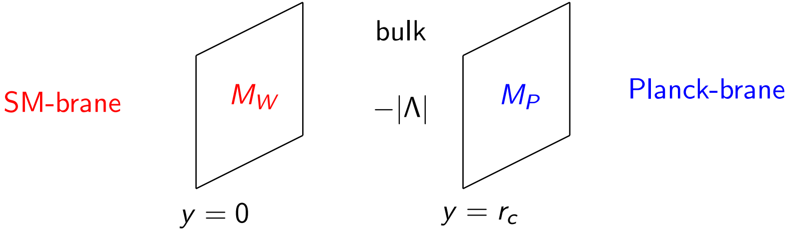
$m_n = c_n\, k\, e^{-2kr_c} \sim$ TeV $\qquad c_n \simeq (n + 1/4)$ for large n

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

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

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

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



- exponential hierarchy: $g_s^2 = e^{-\alpha|y|}$ $\quad M_P^2 \sim \frac{M_5^3}{\alpha} e^{\alpha r_c}$ $\quad \alpha \equiv k_{RS}$
- 4d graviton flat, KK gravitons localized near SM

LST KK graviton phenomenology

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

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

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

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

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

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

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

  $\Rightarrow$ distinct experimental signals

Conclusions

- Possible discovery of the Higgs scalar at the LHC: big step forward
- Precise measurement of its couplings is of primary importance
- hint of Nature's answer to the mass hierarchy question

  and of BSM physics

  - natural or unnatural SUSY?
  - low string scale in some realization?
  - something new and unexpected?
- Good chance that next phase of LHC run will provide the answer