

# Aspects of string phenomenology in the LHC era

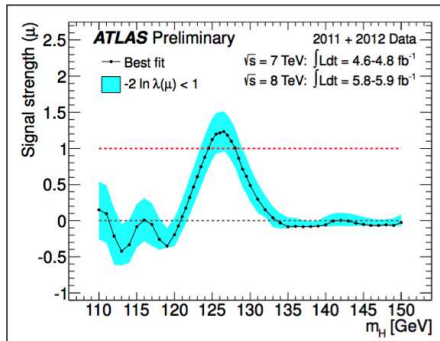
I. Antoniadis



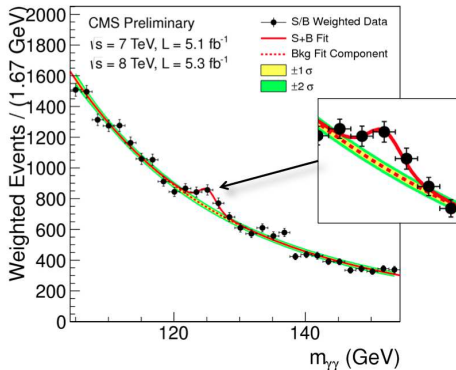
Planck 2013 - Bonn, 20-24 May 2013

- High string scale, SUSY and 125 GeV Higgs
- Live with the hierarchy and extra  $U(1)$ 's
- Low scale strings and extra dimensions

# Higgs boson discovery



$$m_H = 125.5 \pm 0.2 \text{ (stat.)} \pm 0.5 \text{ (syst.)}$$



$$m_H = 125.7 \pm 0.3 \pm 0.3 \text{ GeV}$$

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

Standard picture: low energy supersymmetry

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

## Advantages:

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

## Problems:

- too many parameters: soft breaking terms
- MSSM : already a % - %<sub>00</sub> fine-tuning     'little' hierarchy problem

Inclusive searches	MSUGRA/CMSSM : 0 lep + $\tilde{j}s + E_{T,miss}$	<b>1.80 TeV</b> $\tilde{g} = \tilde{g}$ mass	
	MSUGRA/CMSSM : 1 lep + $\tilde{j}s + E_{T,miss}$	<b>1.24 TeV</b> $\tilde{g} = \tilde{g}$ mass	
3rd gen. gluino mediated	Pheno model : 0 lep + $\tilde{j}s + E_{T,miss}$	<b>1.18 TeV</b> $\tilde{g}$ mass ( $m(\tilde{g}) < 2 \text{ TeV}, \text{light } \tilde{\chi}_2^0$ )	
	Pheno model : 0 lep + $\tilde{j}s + E_{T,miss}$	<b>1.28 TeV</b> $\tilde{g}$ mass ( $m(\tilde{g}) < 2 \text{ TeV}, \text{light } \tilde{\chi}_1^0$ )	
	Glauino med. $\tilde{\chi}^{\pm} (\tilde{g} \rightarrow q\tilde{\chi}^{\pm})$ : 1 lep + $\tilde{j}s + E_{T,miss}$	<b>900 GeV</b> $\tilde{g}$ mass ( $m(\tilde{\chi}_1^{\pm}) < 200 \text{ GeV}, m(\tilde{\chi}_2^0) = \frac{1}{2}m(\tilde{\chi}_1^0) + m(\tilde{g})$ )	
	GMSB (fl NLSP) : 2 lep (OS) + $\tilde{j}s + E_{T,miss}$	<b>1.24 TeV</b> $\tilde{g}$ mass ( $\tan\beta < 15$ )	
	GMSB (r NLSP) : 1-2 $\tau$ + $\tilde{j}s + E_{T,miss}$	<b>1.40 TeV</b> $\tilde{g}$ mass ( $\tan\beta > 18$ )	
	GGM (bino NLSP) : $\gamma\gamma + E_{T,miss}$	<b>1.07 TeV</b> $\tilde{g}$ mass ( $m(\tilde{\chi}_1^0) > 50 \text{ GeV}$ )	
	GGM (wino NLSP) : $\gamma + \text{lep} + E_{T,miss}$	<b>619 GeV</b> $\tilde{g}$ mass	
	GGM (higgsino-bino NLSP) : $\gamma + b + E_{T,miss}$	<b>900 GeV</b> $\tilde{g}$ mass ( $m(\tilde{\chi}_1^0) = 220 \text{ GeV}$ )	
	GGM (higgsino NLSP) : $Z + \text{jets} + E_{T,miss}$	<b>800 GeV</b> $\tilde{g}$ mass ( $m(\tilde{H}^0) > 200 \text{ GeV}$ )	
	Gravitino LSP : 'monojet' + $E_{T,miss}$	<b>845 GeV</b> $F$ scale ( $m(\tilde{G}) > 10^4 eV$ )	
3rd gen. squarks direct production	$\tilde{g} \rightarrow b\tilde{b}^*$ : 0 lep + 3 b-jets + $E_{T,miss}$	<b>1.24 TeV</b> $\tilde{g}$ mass ( $m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ )	
	$\tilde{g} \rightarrow t\tilde{t}^*$ : 2 SS-lep + (0-3b- $\tilde{j}$ s) + $E_{T,miss}$	<b>900 GeV</b> $\tilde{g}$ mass (any $m(\tilde{\chi}_i^0)$ )	
	$\tilde{g} \rightarrow t\tilde{t}^*$ : 0 lep + multi- $\tilde{j}$ s + $E_{T,miss}$	<b>1.00 TeV</b> $\tilde{g}$ mass ( $m(\tilde{\chi}_1^0) < 300 \text{ GeV}$ )	
	$\tilde{g} \rightarrow t\tilde{t}^*$ : 0 lep + 3 b- $\tilde{j}$ s + $E_{T,miss}$	<b>1.18 TeV</b> $\tilde{g}$ mass ( $m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ )	
	$\tilde{b}_1 \rightarrow b\tilde{b}^*$ : 0 lep + 2 b-jets + $E_{T,miss}$	<b>620 GeV</b> $\tilde{b}$ mass ( $m(\tilde{\chi}_1^0) < 120 \text{ GeV}$ )	
	$\tilde{b}_1 \rightarrow b\tilde{t}^*$ : 2 SS-lep + (0-3b- $\tilde{j}$ s) + $E_{T,miss}$	<b>430 GeV</b> $\tilde{b}$ mass ( $m(\tilde{\chi}_1^0) = 2m(\tilde{\chi}_2^0)$ )	
	$\tilde{t}_1 \rightarrow t\tilde{t}^*$ : 1/2 lep + (b-jet) + $E_{T,miss}$	<b>167 GeV</b> $\tilde{t}$ mass ( $m(\tilde{\chi}_1^0) = 55 \text{ GeV}$ )	
	$\tilde{t}_1 \rightarrow t\tilde{b}^*$ : 1 lep + b-jet + $E_{T,miss}$	<b>160-410 GeV</b> $\tilde{t}$ mass ( $m(\tilde{\chi}_1^0) = 0 \text{ GeV}, m(\tilde{\chi}_2^0) = 150 \text{ GeV}$ )	
	$\tilde{t}_1 \rightarrow t\tilde{t}^*$ (medium), $\tilde{t}_1 \rightarrow b\tilde{t}^*$ : 2 lep + $E_{T,miss}$	<b>160-640 GeV</b> $\tilde{t}$ mass ( $m(\tilde{\chi}_1^0) = 0 \text{ GeV}, m(\tilde{\chi}_1^0) = 10 \text{ GeV}$ )	
	$\tilde{t}_1 \rightarrow t\tilde{t}^*$ (heavy), $\tilde{t}_1 \rightarrow b\tilde{t}^*$ : 1 lep + b-jet + $E_{T,miss}$	<b>200-610 GeV</b> $\tilde{t}$ mass ( $m(\tilde{\chi}_1^0) = 0$ )	
	$\tilde{t}_1 \rightarrow t\tilde{t}^*$ (heavy), $\tilde{t}_1 \rightarrow b\tilde{t}^*$ : 0 lep + 6(2b)-jets + $E_{T,miss}$	<b>320-660 GeV</b> $\tilde{t}$ mass ( $m(\tilde{\chi}_1^0) = 0$ )	
	$\tilde{t}_1$ (natural GMSB) : $Z(\rightarrow\mu\mu) + b\text{-jet} + E_{T,miss}$	<b>500 GeV</b> $\tilde{t}$ mass ( $m(\tilde{\chi}_1^0) > 150 \text{ GeV}$ )	
	$\tilde{t}_1 \rightarrow t\tilde{t}^*$ : 1 lep + b-jet + $E_{T,miss}$	<b>520 GeV</b> $\tilde{t}_1$ mass ( $m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0) + 180 \text{ GeV}$ )	
	$\tilde{t}_1 \rightarrow t\tilde{t}^*$ : 2 lep + $E_{T,miss}$	<b>85-195 GeV</b> $\tilde{t}$ mass ( $m(\tilde{\chi}_1^0) = 0$ )	
	$\tilde{\chi}_2^{\pm} \rightarrow \tilde{\chi}_1^0 + W(\rightarrow l\nu)$ : 2 lep + $E_{T,miss}$	<b>116-340 GeV</b> $\tilde{\chi}_2^{\pm}$ mass ( $m(\tilde{\chi}_1^0) < 10 \text{ GeV}, m(\tilde{\nu}_l) = \frac{1}{2}m(\tilde{\chi}_1^0) + m(\tilde{\chi}_2^0)$ )	
	$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + \nu(\tau\nu)$ : 2 $\tau$ + $E_{T,miss}$	<b>180-330 GeV</b> $\tilde{\chi}_2^0$ mass ( $m(\tilde{\chi}_1^0) < 10 \text{ GeV}, m(\tilde{\nu}_l) = \frac{1}{2}m(\tilde{\chi}_1^0) + m(\tilde{\chi}_2^0)$ )	
	$\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 + W(\rightarrow l\nu)$ : 3 lep + $E_{T,miss}$	<b>600 GeV</b> $\tilde{\chi}_1^{\pm}$ mass ( $m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\nu}_l) = 0$ as above)	
	$\tilde{\chi}_1^0 \rightarrow W(\rightarrow l\nu) + Z(\rightarrow l\nu) + E_{T,miss}$	<b>315 GeV</b> $\tilde{\chi}_1^0$ mass ( $m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0$ , sleptons decoupled)	
	Direct $\tilde{\chi}_1^0$ pair prod. (AMSB) : long-lived $\tilde{\chi}_1^0$	<b>220 GeV</b> $\tilde{\chi}_1^0$ mass ( $1 < v(\tilde{\chi}_1^0) < 10 \text{ ns}$ )	
	EW direct	Stable $\tilde{g}$ , R-hadrons : low $\beta$ , low GMSB, stable $\tilde{t}$ : low $\beta$	<b>985 GeV</b> $\tilde{g}$ mass
		GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ : non-pointing photons	<b>300 GeV</b> $\tilde{t}$ mass ( $5 < \tan\beta < 20$ )
		$\tilde{\chi}_1^0 \rightarrow q\bar{q}$ (RPV) : $\mu + \text{heavy displaced vertex}$	<b>230 GeV</b> $\tilde{\chi}_1^0$ mass ( $0.4 < v(\tilde{\chi}_1^0) < 2 \text{ ns}$ )
LFV : $pp \rightarrow \tilde{\nu}_i + X, \tilde{\nu}_i \rightarrow e + \mu + \text{resonance}$		<b>790 GeV</b> $\tilde{q}$ mass ( $1 \text{ mm} < c\tau < 1 \text{ m}, \tilde{g}$ decoupled)	
LFV : $pp \rightarrow \tilde{\nu}_i + X, \tilde{\nu}_i \rightarrow e(\mu) + \tau + \text{resonance}$		<b>1.61 TeV</b> $\tilde{\nu}_i$ mass ( $\lambda_{211} = 0.10, \lambda_{133} = 0.05$ )	
Bilinear RPV CMSSM : 1 lep + 7 $\tilde{j}s + E_{T,miss}$		<b>1.10 TeV</b> $\tilde{\nu}_i$ mass ( $\lambda_{211} = 0.10, \lambda_{133} = 0.05$ )	
$\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 \rightarrow e\nu_\mu e\nu_\mu$ : 4 lep + $E_{T,miss}$		<b>1.2 TeV</b> $\tilde{g}$ mass ( $c\tau_{133} < 1 \text{ mm}$ )	
$\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 \rightarrow \tau\nu, e\nu_\tau$ : 3 lep + 1 $\tau$ + $E_{T,miss}$		<b>760 GeV</b> $\tilde{\chi}_1^0$ mass ( $m(\tilde{\chi}_1^0) > 300 \text{ GeV}, \lambda_{133} > 0$ )	
$\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + \tau\nu, e\nu_\tau$ : 3 lep + 1 $\tau$ + $E_{T,miss}$		<b>350 GeV</b> $\tilde{\chi}_1^0$ mass ( $m(\tilde{\chi}_1^0) > 80 \text{ GeV}, \lambda_{133} > 0$ )	
$\tilde{g} \rightarrow q\bar{q}$ : 3-jet resonance pair		<b>666 GeV</b> $\tilde{g}$ mass	
$\tilde{g} \rightarrow t\bar{t}$ : 2 SS-lep + (0-3b- $\tilde{j}$ s) + $E_{T,miss}$	<b>880 GeV</b> $\tilde{g}$ mass (any $m(\tilde{\chi}_i^0)$ )		
Long-lived particles	Scalar gluon : 2-jet resonance pair	<b>100-287 GeV</b> sgluon mass (incl. limit from 1110.2693)	
	WIMP interaction (D5, Dirac $\tilde{\chi}$ ) : 'monojet' + $E_{T,miss}$	<b>704 GeV</b> $M^*$ scale ( $m_* < 80 \text{ GeV}$ , limit of $< 687 \text{ GeV}$ for D8)	

$$\int L dt = (4.4 - 20.7) \text{ fb}^{-1}$$

$$\sqrt{s} = 7, 8 \text{ TeV}$$

**8 TeV, all 2012 data**

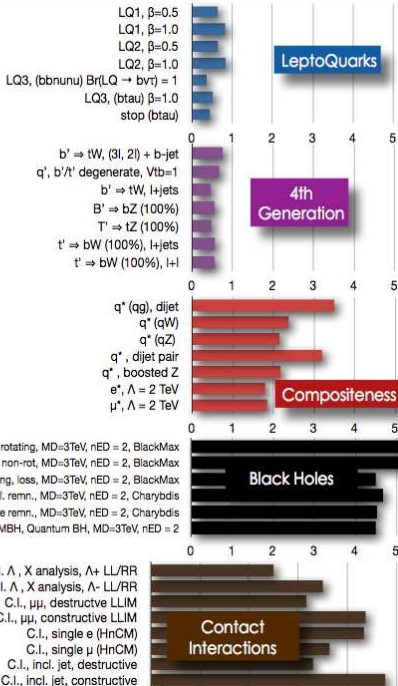
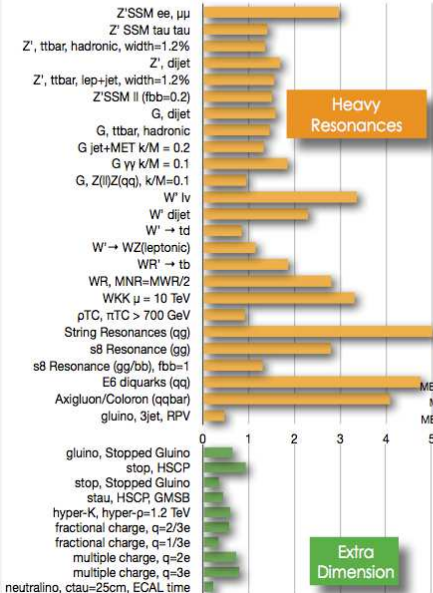
**8 TeV, partial 2012 data**

**7 TeV, all 2011 data**

\*Only a selection of the available mass limits on new states or phenomena shown. All limits quoted are observed minus 1 $\sigma$  theoretical signal cross section uncertainty.

# CMS EXOTICA

95% CL EXCLUSION LIMITS (TeV)

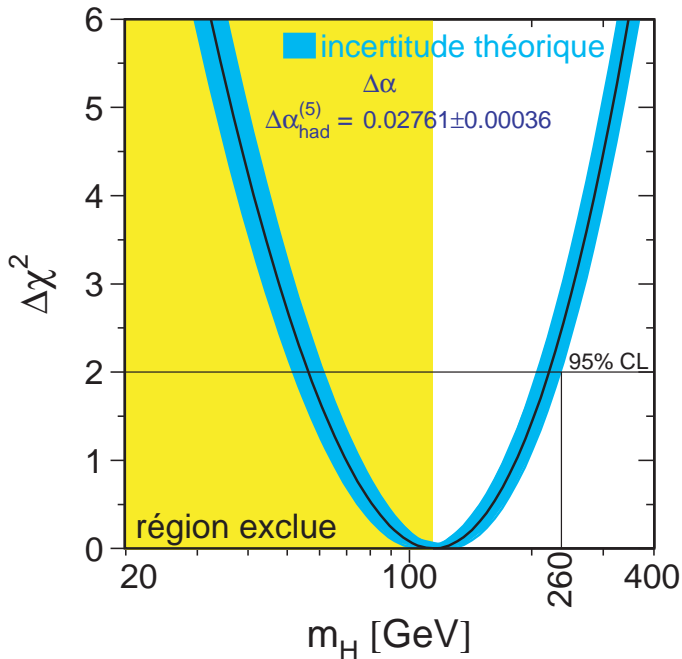


# Remarks on the value of the Higgs mass $\sim 125$ GeV

- 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 [8]  
early to draw a general conclusion before LHC13/14  
e.g. an extra singlet or split families can alleviate the fine tuning [9]
- very important to measure its properties and couplings [13]  
any deviation of its couplings to top, bottom and EW gauge bosons  
implies new light states involved in the EWSB altering the fine-tuning



# Fine-tuning in MSSM

Upper bound on the lightest scalar mass:

$$m_h^2 \lesssim m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2} \frac{m_t^4}{v^2} \left[ \ln \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2} \left( 1 - \frac{A_t^2}{12m_{\tilde{t}}^2} \right) \right] \lesssim (130 \text{ GeV})^2$$

$$m_h \simeq 126 \text{ GeV} \Rightarrow m_{\tilde{t}} \simeq 3 \text{ TeV or } A_t \simeq 3m_{\tilde{t}} \simeq 1.5 \text{ TeV}$$

$\Rightarrow$  % to a few ‰ fine-tuning

$$\text{minimum of the potential: } m_Z^2 = 2 \frac{m_1^1 - m_2^2 \tan^2 \beta}{\tan^2 \beta - 1} \sim -2m_2^2 + \dots$$

$$\text{RG evolution: } m_2^2 = m_2^2(M_{\text{GUT}}) - \frac{3\lambda_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln \frac{M_{\text{GUT}}}{m_{\tilde{t}}} + \dots \quad [23]$$

$$\sim m_2^2(M_{\text{GUT}}) - \mathcal{O}(1)m_{\tilde{t}}^2 + \dots \quad [6]$$



# 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:

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

$\eta_1$  : generated for instance by a singlet

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

Strumia '99 ; Brignole-Casas-Espinosa-Navarro '03

Dine-Seiberg-Thomas '07

$\eta_1$  : corresponding soft breaking term      spurion  $S \equiv m_S \theta^2$

# Physical consequences of MSSM<sub>5</sub>: Scalar potential

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

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

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

only  $\eta_2$  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:  $\propto \eta_1^2$

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

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

Bernal-Blum-Nir-Losada '09

# MSSM Higgs 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 SUSY)  $\Rightarrow$

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

constant receiving contributions from several operators

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

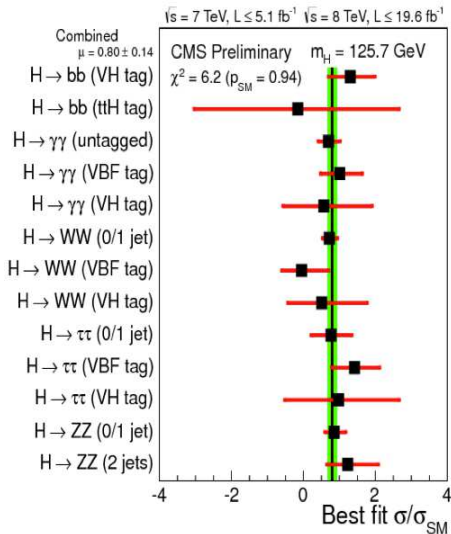
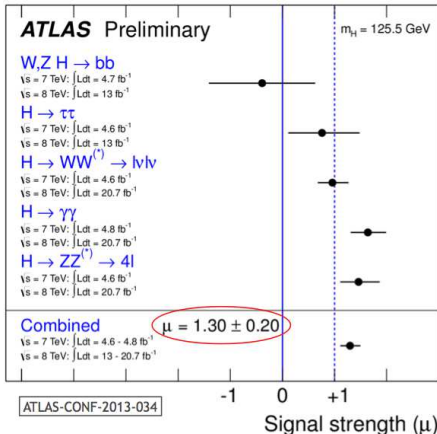
$m_S = 1 \text{ TeV}, M = 10 \text{ TeV}, f_0 \sim 1 - 2.5$  for each operator

$\Rightarrow m_h \simeq 103 - 119 \text{ GeV}$

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

possible resolution of the MSSM fine-tuning problem [6]

# Couplings of the new boson vs SM

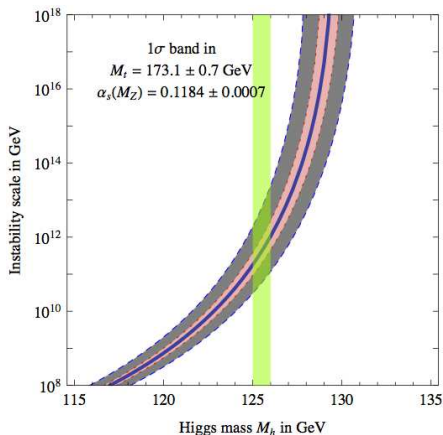
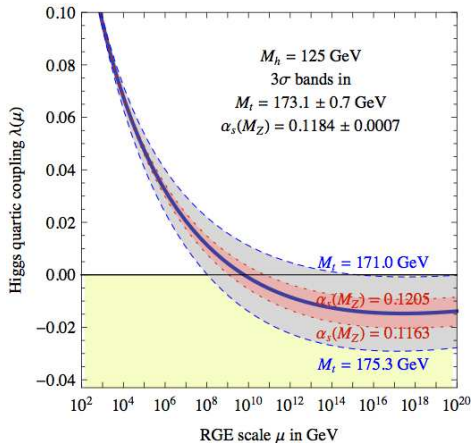


exclusion : spin 2 and pseudoscalar at  $\gtrsim 95\%$  CL

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

# 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

If the weak scale is tuned  $\Rightarrow$  split supersymmetry is a possibility

Arkani Hamed-Dimopoulos '04, Giudice-Romanino '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

$m_S \sim \text{few} - \text{thousands TeV}$

gauginos: a loop factor lighter than scalars ( $\sim m_{3/2}$ )

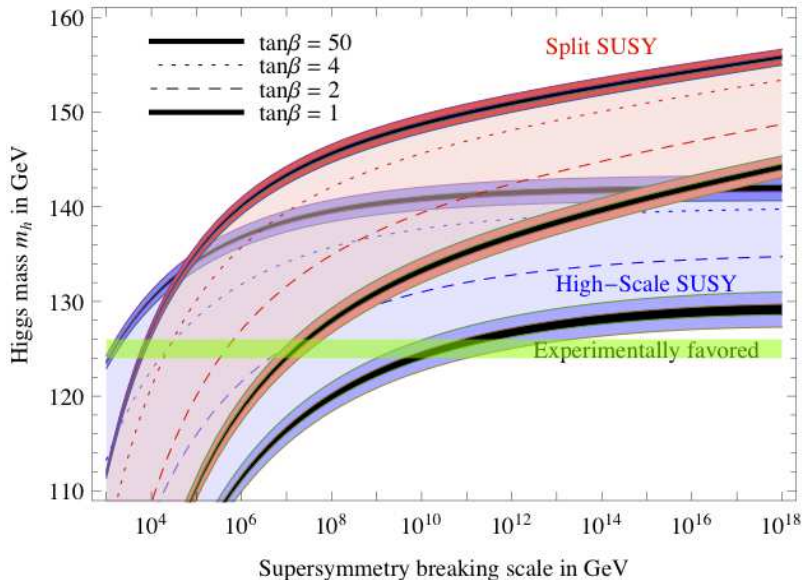
- natural string framework: intersecting (or magnetized) branes

IA-Dimopoulos '04

D-brane stacks are supersymmetric with massless gauginos

intersections have chiral fermions with broken SUSY & massive scalars

## Predicted range for the Higgs mass



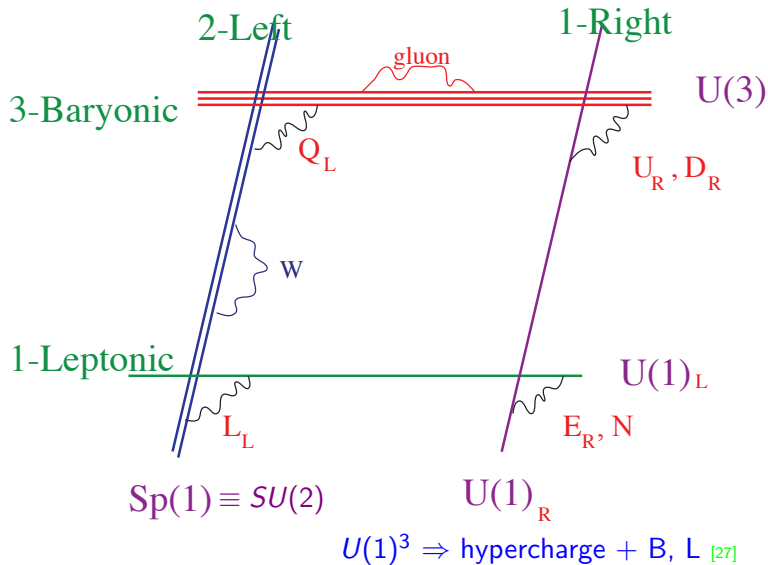


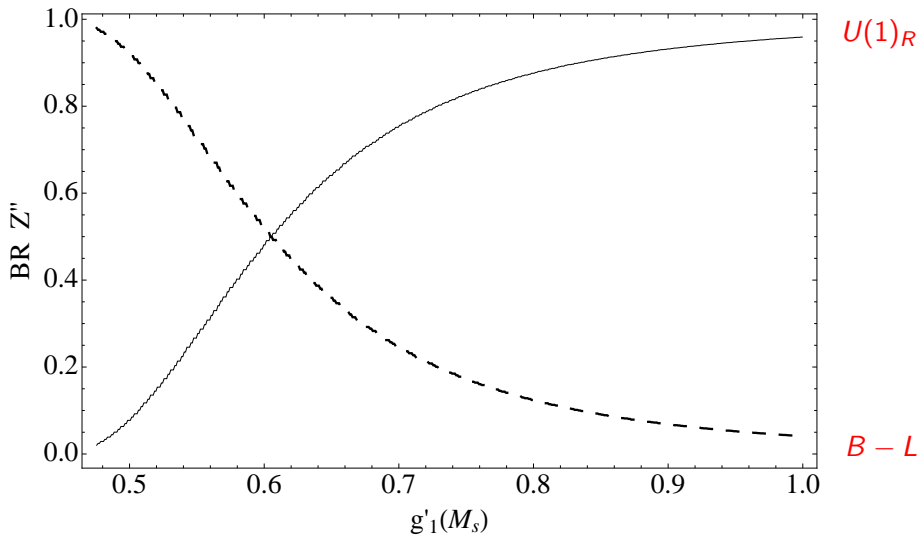
# An extra $U(1)$ can also cure the instability problem

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

- $B$  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  $\Rightarrow 0.5 \lesssim g_{U(1)_R} \lesssim 1$
- present LHC limits:  $m_{Z''} \gtrsim 3 - 4$  TeV (for  $Z'' \simeq B - L$  or  $U(1)_R$ )
- interesting LHC phenomenology and cosmology [20]

# Standard Model on D-branes : SM<sup>++</sup>





- 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  $\nu$ -number close to 4 \*  
→ use the 3  $\nu_R$ 's interacting with SM fermions via  $Z''$   
data: their decoupling during the quark-hadron transition  
⇒  $3.5 \lesssim M_{Z''} \lesssim 7 \text{ TeV}$  (within LHC14 discovery potential)

\* before Planck results

Scalar potential:

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

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

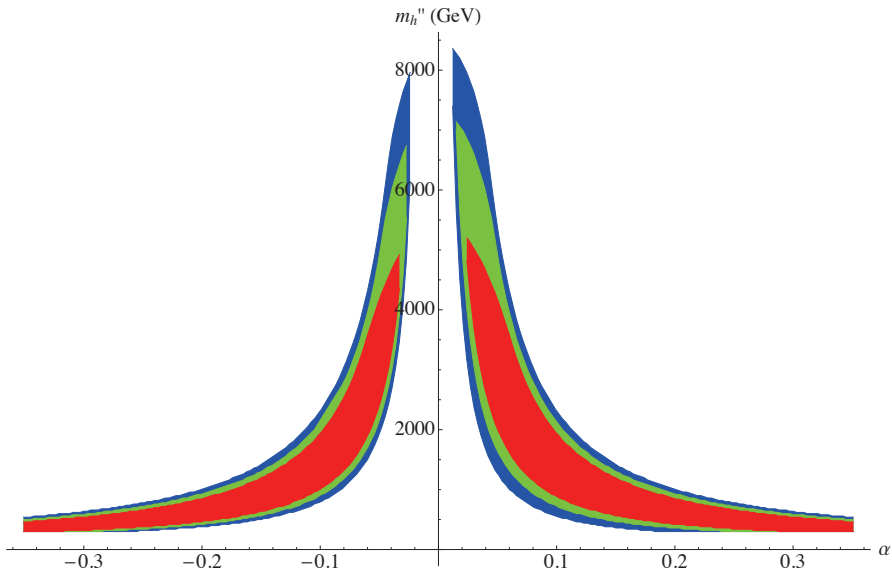
$\Rightarrow$  3 free parameters :  $m_{h''}, \alpha, v'' \leftrightarrow M_{Z''}$

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<sup>++</sup>

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

$$M_{Z''} = 4.5 \text{ TeV}; \quad M_S = 10^{14}, 10^{16}, 10^{19} \text{ GeV}$$



## Alternative answer: Low UV cutoff $\Lambda \sim \text{TeV}$

- low scale gravity  $\Rightarrow$  extra dimensions: large flat or warped
- low string scale  $\Rightarrow$  low scale gravity, ultra weak string coupling

$M_s \sim 1 \text{ TeV} \Rightarrow$  volume  $R_{\perp}^n = 10^{32} l_s^n$  ( $R_{\perp} \sim .1 - 10^{-13} \text{ mm}$  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 [8]

$\Lambda \sim$  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

# 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:  $\lambda = \frac{1}{8}(g_2^2 + g'^2)$

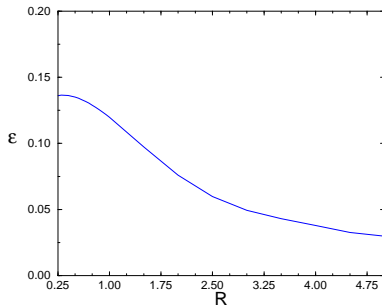
D-terms

$\mu^2 = -g^2 \epsilon^2 M_5^2 \leftarrow$  effective UV cutoff

$$\epsilon^2(R) = \frac{R^3}{2\pi^2} \int_0^\infty dl l^{3/2} \frac{\theta_2^4}{16l^4 \eta^{12}} \left( il + \frac{1}{2} \right) \sum_n n^2 e^{-2\pi n^2 R^2 l}$$

UV  $\nearrow$   $\searrow$  IR  $\nearrow$   $\searrow$   $e^{-\pi l}$   $1$





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

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

Higgs scalar = component of a higher dimensional gauge field

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

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

$M_s$  or  $1/R \sim$  a few or several TeV [29]

# Accelerator signatures: 4 different scales

- Gravitational radiation in the bulk  $\Rightarrow$  missing energy

present LHC bounds:  $M_* \gtrsim 2.5 - 4$  TeV

- Massive string vibrations  $\Rightarrow$  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

present LHC limits:  $M_s \gtrsim 5$  TeV

- Large TeV dimensions  $\Rightarrow$  KK resonances of SM gauge bosons I.A. '90

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

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

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

masses suppressed by a loop factor from  $M_s$

# 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)

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

or massless in the absence of such anomalies [18]

- $B$  and  $L$  become massive due to anomalies

Green-Schwarz terms

- the global symmetries remain in perturbation

- Baryon number  $\Rightarrow$  proton stability

- Lepton number  $\Rightarrow$  protect small neutrino masses

no Lepton number  $\Rightarrow \frac{1}{M_s} LLHH \rightarrow$  Majorana mass:  $\frac{\langle H \rangle^2}{M_s} LL$

$\sim$  GeV

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

with possible leptophobic couplings leading to CDF-type  $Wjj$  events

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

# 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?
- LHC enters a new era with possible new discoveries