Mass hierarchy and electroweak symmetry breaking

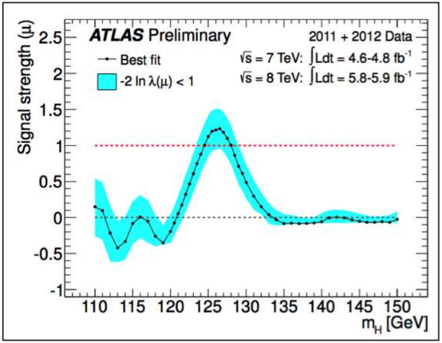
I. Antoniadis

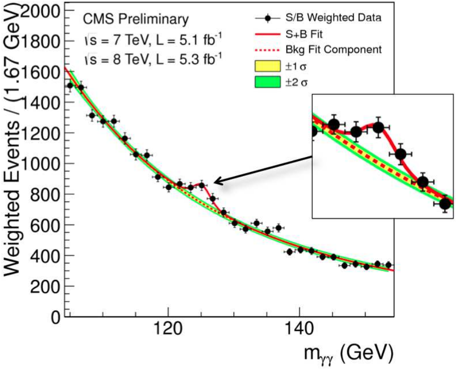
Beyond the Standard Model after the first run of LHC

GGI, Florence, 9-12 July 2013

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

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

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

Standard picture: low energy supersymmetry

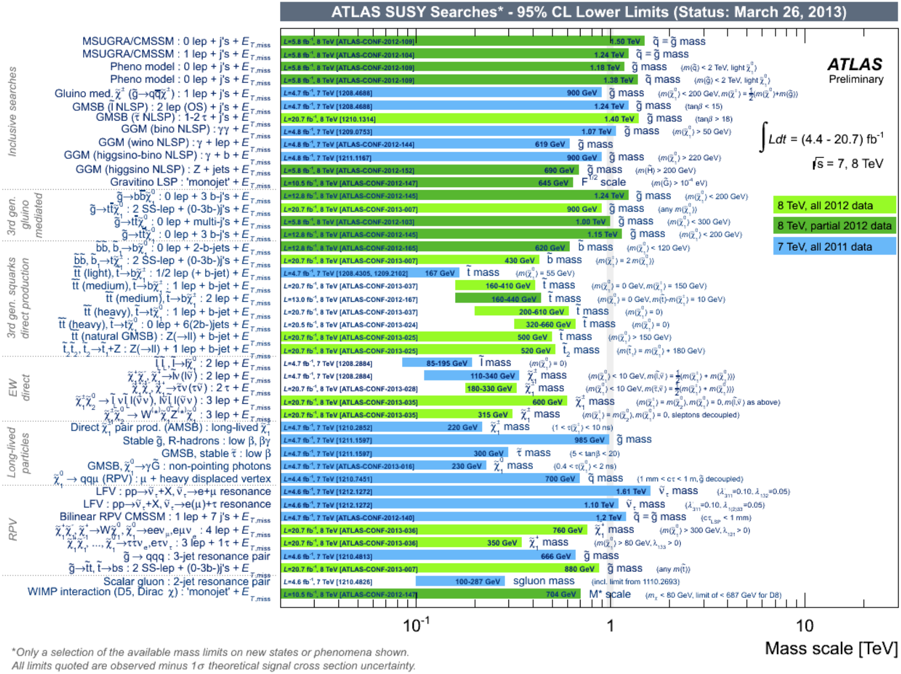
Natural framework: Heterotic string (or high-scale M/F) theory

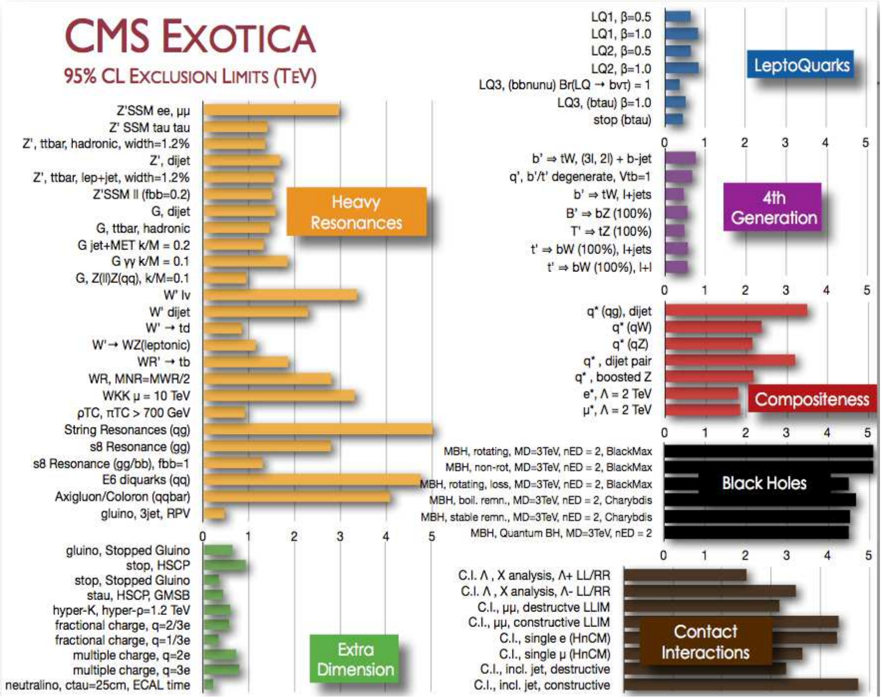
Advantages:

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

Problems:

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


ATLAS SUSY Searches* - 95% CL Lower Limits (Status: March 26, 2013)
ATLAS
Preliminary
$\int L dt = (4.4 - 20.7)\ fb^{-1}$
$\sqrt{s}$ = 7, 8 TeV
8 TeV, all 2012 data
8 TeV, partial 2012 data
7 TeV, all 2011 data
Inclusive searches
3rd gen. gluino mediated
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
MSUGRA/CMSSM : 0 lep + j's + $E_{T,miss}$ — 1.50 TeV $\tilde{q} = \tilde{g}$ mass
MSUGRA/CMSSM : 1 lep + j's + $E_{T,miss}$ — 1.24 TeV $\tilde{q} = \tilde{g}$ mass
Pheno model : 0 lep + j's + $E_{T,miss}$ — 1.18 TeV $\tilde{g}$ mass
Pheno model : 0 lep + j's + $E_{T,miss}$ — 1.38 TeV $\tilde{q}$ mass
Gluino med. $\tilde{\chi}^\pm$ ($\tilde{g} \to q\bar{q}\tilde{\chi}^\pm$) : 1 lep + j's + $E_{T,miss}$ — 900 GeV $\tilde{g}$ mass
GMSB ($\tilde{l}$ NLSP) : 2 lep (OS) + j's + $E_{T,miss}$ — 1.24 TeV $\tilde{g}$ mass
GMSB ($\tilde{\tau}$ NLSP) : 1-2 τ + j's + $E_{T,miss}$ — 1.40 TeV $\tilde{g}$ mass
GGM (bino NLSP) : $\gamma\gamma$ + $E_{T,miss}$ — 1.07 TeV $\tilde{g}$ mass
GGM (wino NLSP) : γ + lep + $E_{T,miss}$ — 619 GeV $\tilde{g}$ mass
GGM (higgsino-bino NLSP) : γ + b + $E_{T,miss}$ — 900 GeV $\tilde{g}$ mass
GGM (higgsino NLSP) : Z + jets + $E_{T,miss}$ — 690 GeV $\tilde{g}$ mass
Gravitino LSP : 'monojet' + $E_{T,miss}$ — 645 GeV $F^{1/2}$ scale
$\tilde{g} \to b\bar{b}\tilde{\chi}^0_1$: 0 lep + 3 b-j's + $E_{T,miss}$ — 1.24 TeV $\tilde{g}$ mass
$\tilde{g} \to t\bar{t}\tilde{\chi}^0_1$: 2 SS-lep + (0-3b-)j's + $E_{T,miss}$ — 900 GeV $\tilde{g}$ mass
$\tilde{g} \to t\bar{t}\tilde{\chi}^0_1$: 0 lep + multi-j's + $E_{T,miss}$ — 1.00 TeV $\tilde{g}$ mass
$\tilde{g} \to t\bar{t}\tilde{\chi}^0_1$: 0 lep + 3 b-j's + $E_{T,miss}$ — 1.15 TeV $\tilde{g}$ mass
$\tilde{b}\tilde{b}$, $\tilde{b}_1 \to b\tilde{\chi}^0_1$: 0 lep + 2-b-jets + $E_{T,miss}$ — 620 GeV $\tilde{b}$ mass
$\tilde{b}\tilde{b}$, $\tilde{b}_1 \to t\tilde{\chi}^\pm_1$: 2 SS-lep + (0-3b-)j's + $E_{T,miss}$ — 430 GeV $\tilde{b}$ mass
$\tilde{t}\tilde{t}$ (light), $\tilde{t}_1 \to b\tilde{\chi}^\pm_1$: 1/2 lep (+ b-jet) + $E_{T,miss}$ — 167 GeV $\tilde{t}$ mass
$\tilde{t}\tilde{t}$ (medium), $\tilde{t}_1 \to b\tilde{\chi}^\pm_1$: 1 lep + b-jet + $E_{T,miss}$ — 160-410 GeV $\tilde{t}$ mass
$\tilde{t}\tilde{t}$ (medium), $\tilde{t}_1 \to b\tilde{\chi}^\pm_1$: 2 lep + $E_{T,miss}$ — 160-440 GeV $\tilde{t}$ mass
$\tilde{t}\tilde{t}$ (heavy), $\tilde{t}_1 \to t\tilde{\chi}^0_1$: 1 lep + b-jet + $E_{T,miss}$ — 200-610 GeV $\tilde{t}$ mass
$\tilde{t}\tilde{t}$ (heavy), $\tilde{t}_1 \to t\tilde{\chi}^0_1$: 0 lep + 6(2b-)jets + $E_{T,miss}$ — 320-660 GeV $\tilde{t}$ mass
$\tilde{t}\tilde{t}$ (natural GMSB) : Z($\to$ll) + b-jet + $E_{T,miss}$ — 500 GeV $\tilde{t}$ mass
$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2 \to \tilde{t}_1$+Z : Z($\to$ll) + 1 lep + b-jet + $E_{T,miss}$ — 520 GeV $\tilde{t}_2$ mass
$\tilde{l}_L\tilde{l}_L$, $\tilde{l} \to l\tilde{\chi}^0_1$: 2 lep + $E_{T,miss}$ — 85-195 GeV $\tilde{l}$ mass
$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1 \to \tilde{l}\nu(l\tilde{\nu})$: 2 lep + $E_{T,miss}$ — 110-340 GeV $\tilde{\chi}^\pm_1$ mass
$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1 \to \tilde{\tau}\nu(\tau\tilde{\nu})$: 2 τ + $E_{T,miss}$ — 180-330 GeV $\tilde{\chi}^\pm_1$ mass
$\tilde{\chi}^\pm_1\tilde{\chi}^0_2 \to \tilde{l}_L\nu\tilde{l}_L l(\tilde{\nu}\nu), l\tilde{\nu}\tilde{l}_L l(\tilde{\nu}\nu)$: 3 lep + $E_{T,miss}$ — 600 GeV $\tilde{\chi}^\pm_1$ mass
$\tilde{\chi}^\pm_1\tilde{\chi}^0_2 \to W^{(*)}\tilde{\chi}^0_1 Z^{(*)}\tilde{\chi}^0_1$: 3 lep + $E_{T,miss}$ — 315 GeV $\tilde{\chi}^\pm_1$ mass
Direct $\tilde{\chi}^\pm_1$ pair prod. (AMSB) : long-lived $\tilde{\chi}^\pm_1$ — 220 GeV $\tilde{\chi}^\pm_1$ mass
Stable $\tilde{g}$, R-hadrons : low β, $\beta\gamma$ — 985 GeV $\tilde{g}$ mass
GMSB, stable $\tilde{\tau}$: low β — 300 GeV $\tilde{\tau}$ mass
GMSB, $\tilde{\chi}^0_1 \to \gamma\tilde{G}$: non-pointing photons — 230 GeV $\tilde{\chi}^0_1$ mass
$\tilde{\chi}^0_1 \to qq\mu$ (RPV) : μ + heavy displaced vertex — 700 GeV $\tilde{q}$ mass
LFV : pp$\to\tilde{\nu}_\tau$+X, $\tilde{\nu}_\tau \to e+\mu$ resonance — 1.61 TeV $\tilde{\nu}_\tau$ mass
LFV : pp$\to\tilde{\nu}_\tau$+X, $\tilde{\nu}_\tau \to e(\mu)+\tau$ resonance — 1.10 TeV $\tilde{\nu}_\tau$ mass
Bilinear RPV CMSSM : 1 lep + 7 j's + $E_{T,miss}$ — 1.2 TeV $\tilde{q} = \tilde{g}$ mass
$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1 \to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1 \to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$: 4 lep + $E_{T,miss}$ — 760 GeV $\tilde{\chi}^\pm_1$ mass
$\tilde{l}_L\tilde{l}_L$, ..., $\tilde{\chi}^0_1 \to \tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$: 3 lep + 1τ + $E_{T,miss}$ — 350 GeV $\tilde{\chi}^\pm_1$ mass
$\tilde{g} \to qqq$: 3-jet resonance pair — 666 GeV $\tilde{g}$ mass
$\tilde{g} \to \tilde{t}t$, $\tilde{t} \to bs$: 2 SS-lep + (0-3b-)j's + $E_{T,miss}$ — 880 GeV $\tilde{g}$ mass
Scalar gluon : 2-jet resonance pair — 100-287 GeV sgluon mass
WIMP interaction (D5, Dirac χ) : 'monojet' + $E_{T,miss}$ — 704 GeV M* scale
10^{-1}
1
10
Mass scale [TeV]
*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
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)
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
Compositeness
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
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
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
0 1 2 3 4 5

Remarks on the value of the Higgs mass ~ 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]

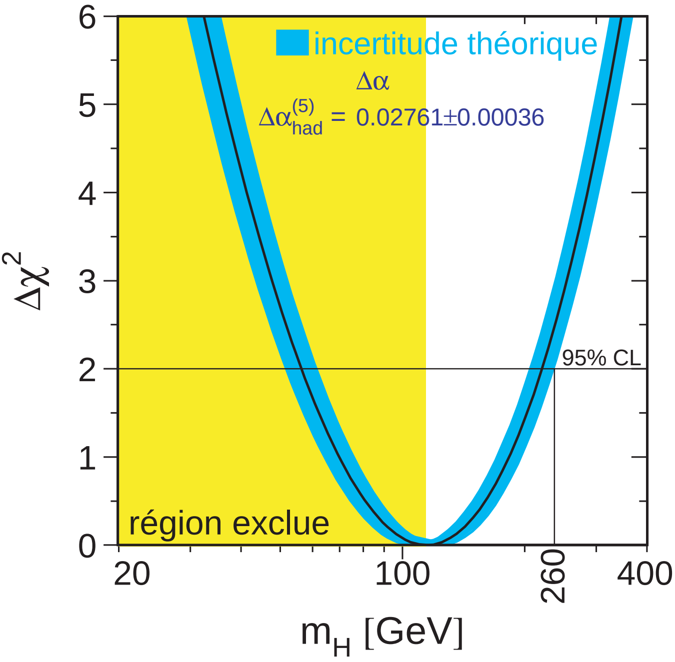
  early to draw a general conclusion before LHC13/14

  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


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: $m_2^2 = m_2^2(M_{\rm GUT}) - \dfrac{3\lambda_t^2}{4\pi^2} m_{\tilde t}^2 \ln\dfrac{M_{\rm GUT}}{m_{\tilde t}} + \cdots$ [25]

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

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

η_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

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 $\not{S}\!USY$) $\Rightarrow$

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

constant receiving contributions from several operators

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

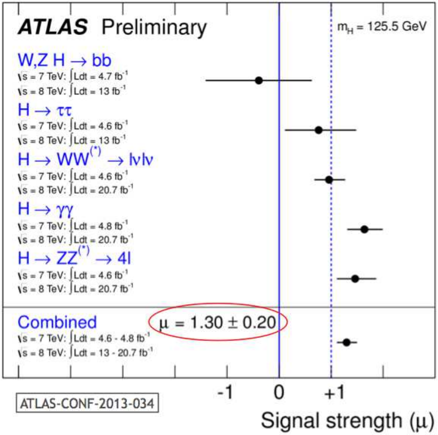
$m_S = 1$ TeV, $M = 10$ TeV, $f_0 \sim 1 - 2.5$ for each operator

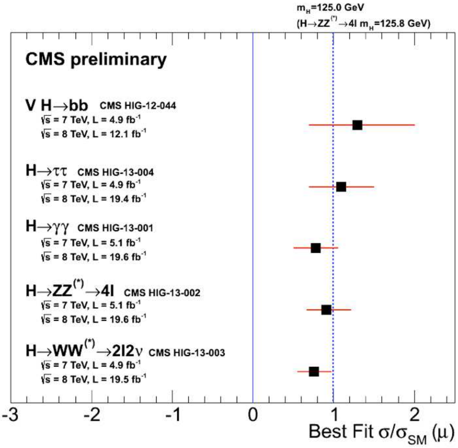
$\Rightarrow m_h \simeq 103 - 119$ GeV

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

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

Couplings of the new boson vs SM



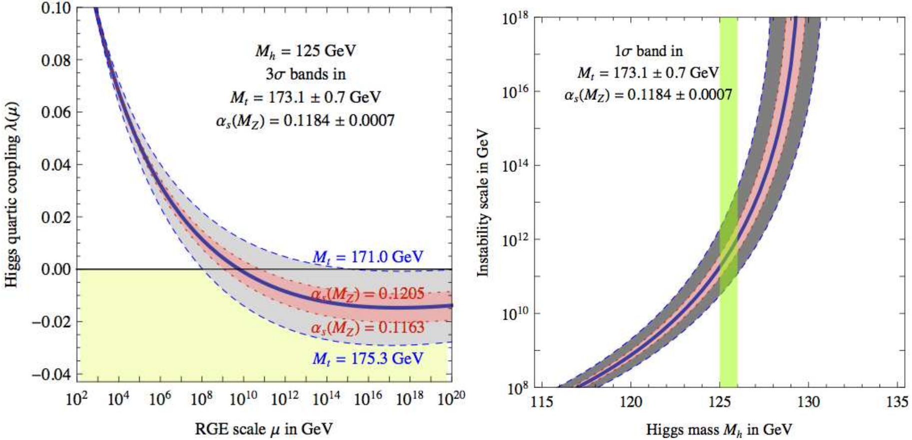


exclusion : spin 2 and pseudoscalar at $\gtrsim$ 95% CL

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



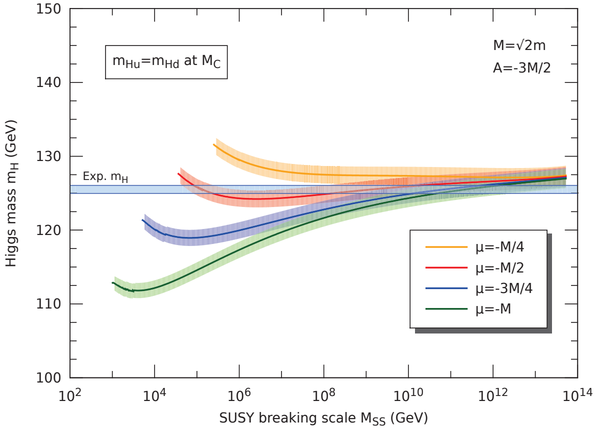
Instability of the SM Higgs potential $\Rightarrow$ metastability of the EW vacuum

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

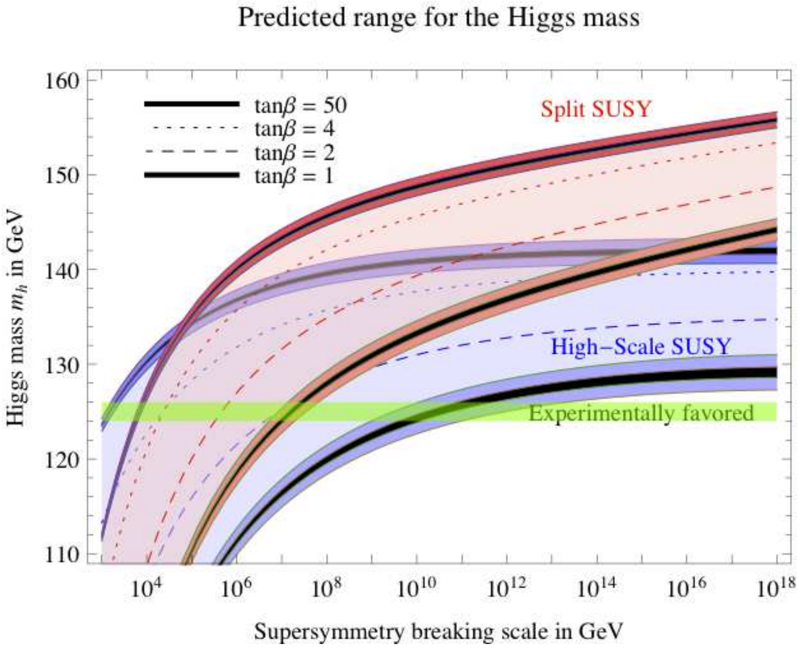
  gauginos: a loop factor lighter than scalars ($\sim m_{3/2}$)
- natural string framework: intersecting (or magnetized) branes

  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

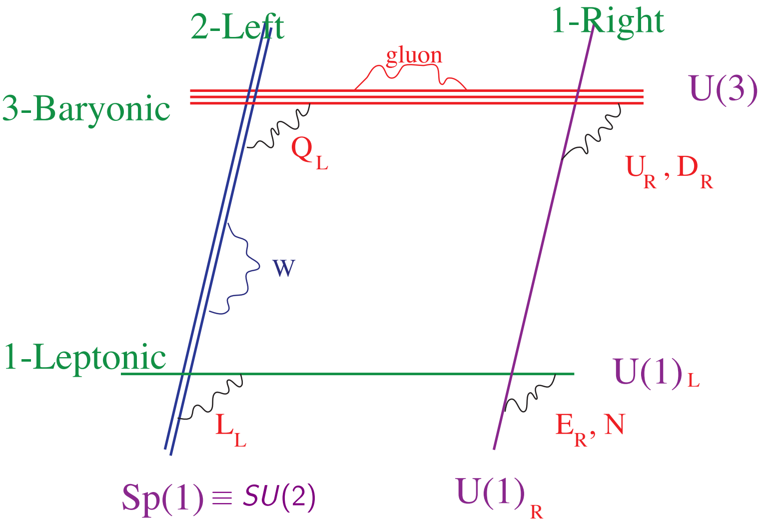
Anchordoqui-IA-Goldberg-Huang-Lüst-Taylor-Vlcek '12

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

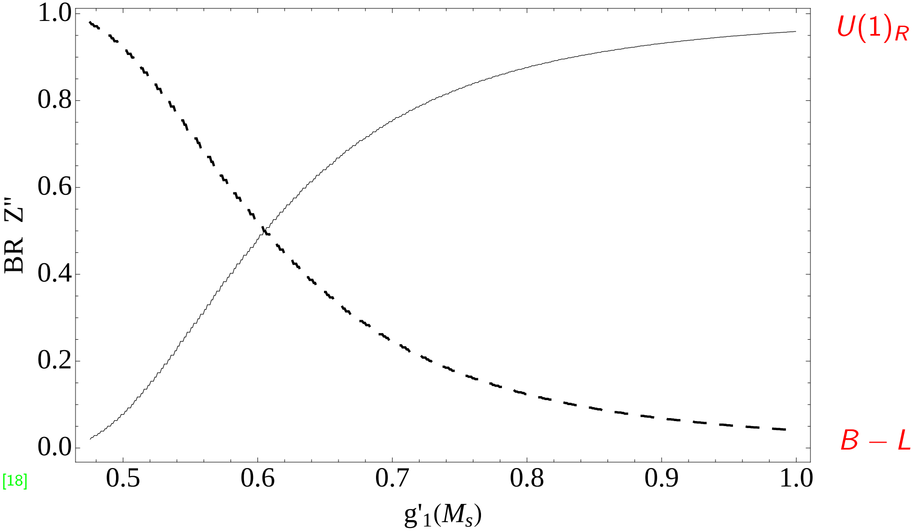
- B anomalous and superheavy
- $B - L$ massless at the string scale (no associated 6d anomaly)

  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 $\Rightarrow 0.5 \lesssim g_{U(1)_R} \lesssim 1$ [20]
- interesting LHC phenomenology and cosmology [21]

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



$U(1)^3 \Rightarrow$ hypercharge + B, L [30]



[18]

- 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

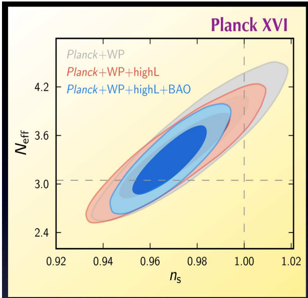
  dark radiation parametrized by an effective ν-number close to 4 *

  $\to$ 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



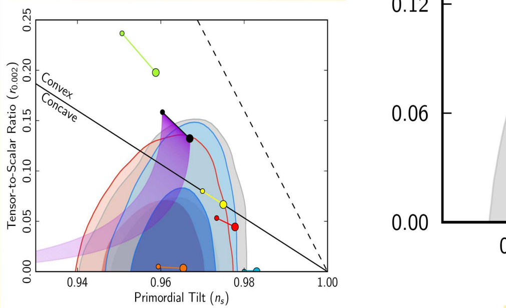
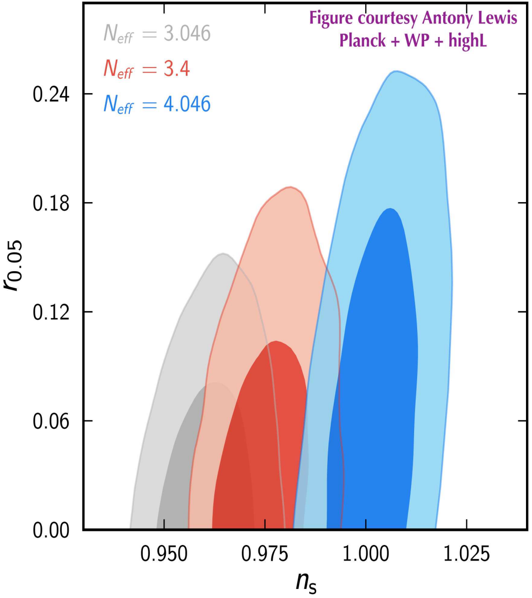


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.



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

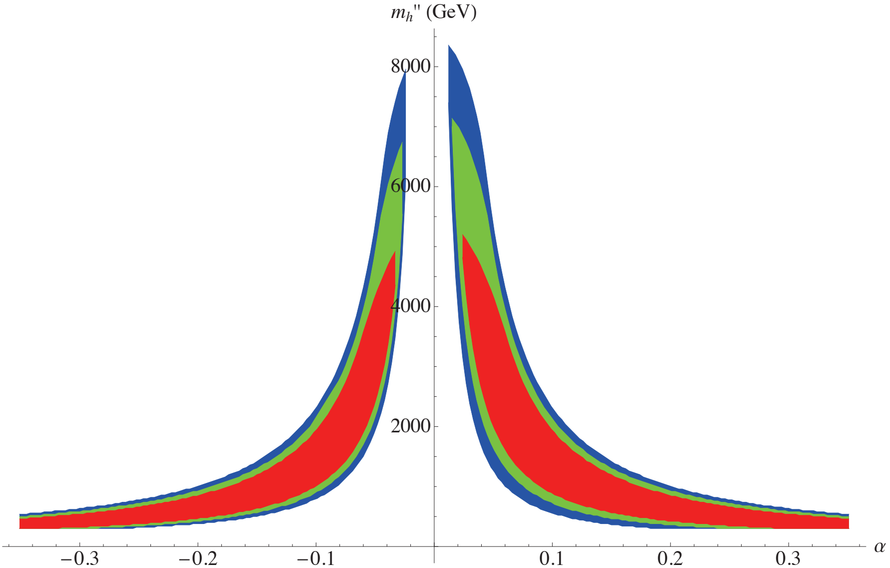
$\Rightarrow$ 3 free parameters : $m_{h''}, \alpha, v'' \leftrightarrow M_{Z''}$

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; $\quad M_s = 10^{14},\ 10^{16},\ 10^{19}$ 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 $R_\perp^n = 10^{32}\, l_s^n$ ($R_\perp \sim .1 - 10^{-13}$ 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 [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

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

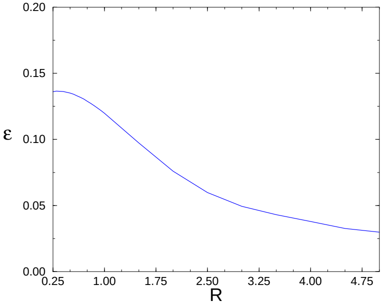
$\mu^2 = 0$ at tree but becomes < 0 at one loop — non-susy vacuum

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

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

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



$R \to 0$: $\varepsilon(R) \simeq 0.14$ 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 $\Rightarrow$ missing energy

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

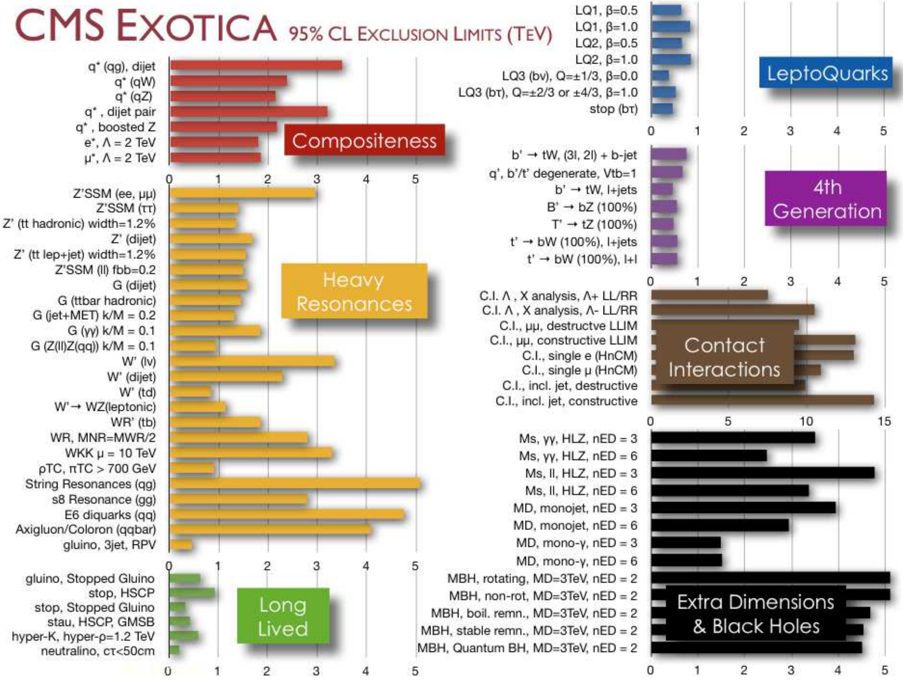
- Large TeV dimensions $\Rightarrow$ KK resonances of SM gauge bosons I.A. '90

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

  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 [30]


CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
Compositeness
Z'SSM (ee, μμ)
Z'SSM (ττ)
Z' (tt hadronic) width=1.2%
Z' (dijet)
Z' (tt 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)
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
neutralino, cτ<50cm
Long Lived
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3 (bν), Q=±1/3, β=0.0
LQ3 (bτ), Q=±2/3 or ±4/3, β=1.0
stop (bτ)
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
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
Ms, γγ, HLZ, nED = 3
Ms, γγ, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-γ, nED = 3
MD, mono-γ, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, non-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2
Extra Dimensions & Black Holes

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 [19]

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

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