Mass hierarchy and electroweak symmetry breaking

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SCALARS 2013

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

particle listing

H^0 (Higgs Boson)

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

H^0 MASS

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

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

Entrance of the Higgs Boson in the Particle Data Group 2013

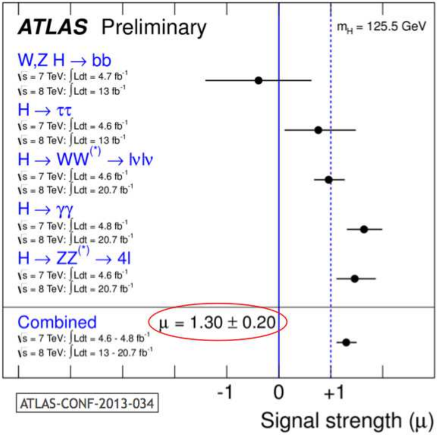
summary tables

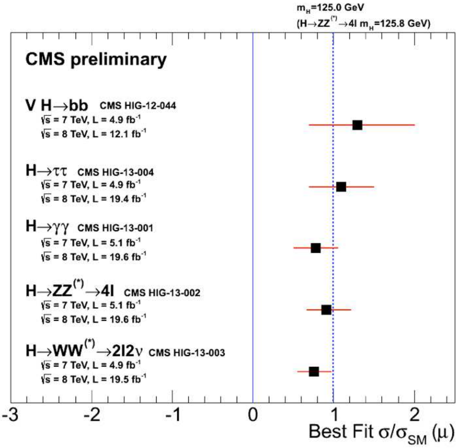
H^0 Mass $m = 125.9 \pm 0.4$ GeV

H^0 signal strengths in different channels [n]

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

Couplings of the new boson vs SM





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

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

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

Standard picture: low energy supersymmetry

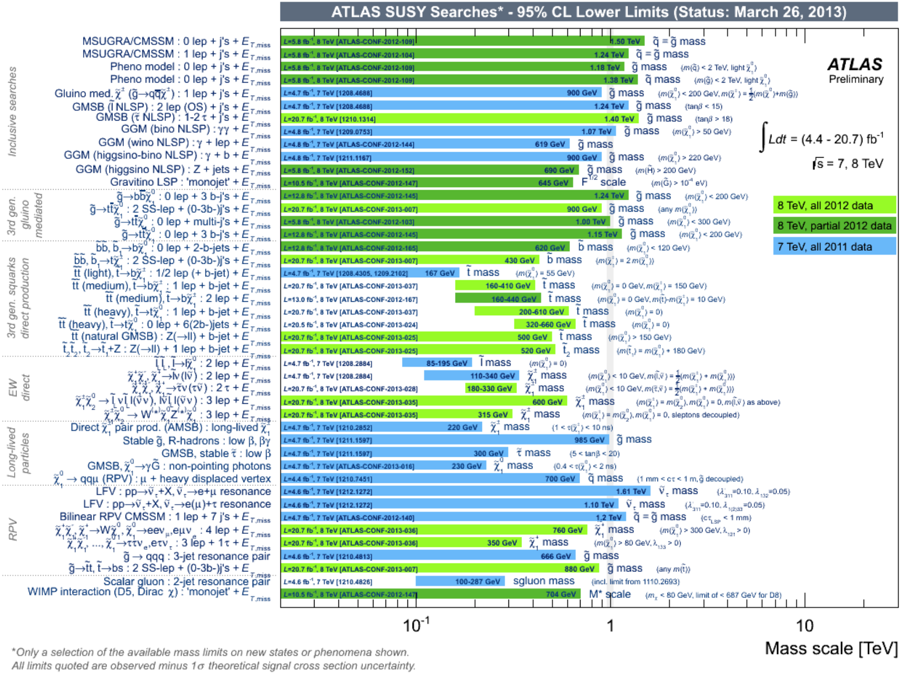
Advantages:

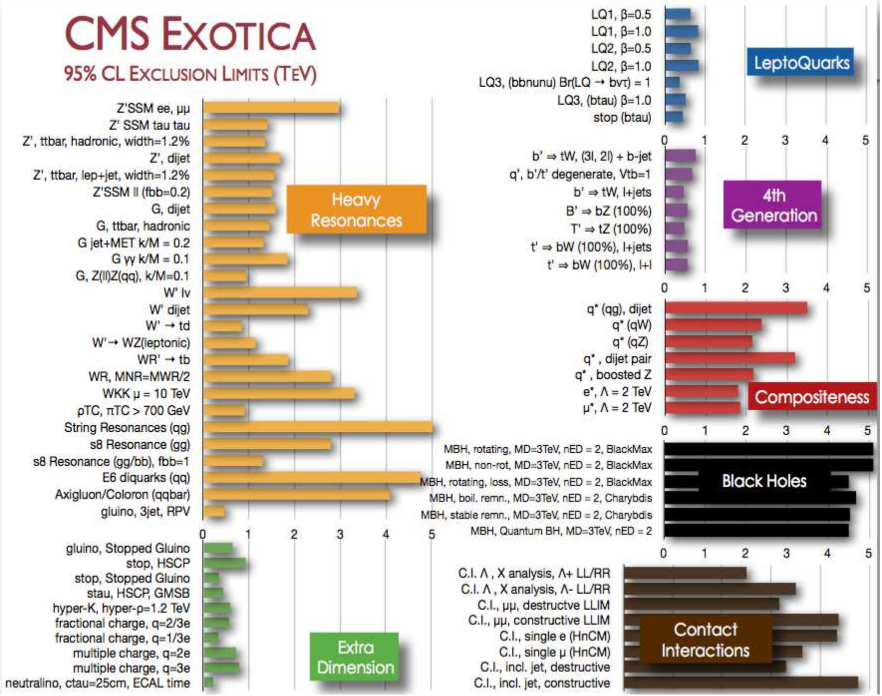
- natural elementary scalars
- gauge coupling unification
- LSP: natural dark matter candidate
- radiative EWSB

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


ATLAS SUSY Searches* - 95% CL Lower Limits (Status: March 26, 2013)
ATLAS
Preliminary
∫Ldt = (4.4 - 20.7) fb⁻¹
√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 — L=5.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-109] — 1.50 TeV q̃ = g̃ mass
MSUGRA/CMSSM : 1 lep + j's + E_T,miss — L=5.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-104] — 1.24 TeV q̃ = g̃ mass
Pheno model : 0 lep + j's + E_T,miss — L=5.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-109] — 1.18 TeV g̃ mass
Pheno model : 0 lep + j's + E_T,miss — L=5.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-109] — 1.38 TeV q̃ mass
Gluino med. χ̃± (g̃→qq̄χ̃±) : 1 lep + j's + E_T,miss — L=4.7 fb⁻¹, 7 TeV [1208.4688] — 900 GeV g̃ mass
GMSB (l̃ NLSP) : 2 lep (OS) + j's + E_T,miss — L=4.7 fb⁻¹, 7 TeV [1208.4688] — 1.24 TeV g̃ mass (tanβ < 15)
GMSB (τ̃ NLSP) : 1-2 τ + j's + E_T,miss — L=20.7 fb⁻¹, 8 TeV [1210.1314] — 1.40 TeV g̃ mass (tanβ > 18)
GGM (bino NLSP) : γγ + E_T,miss — L=4.8 fb⁻¹, 7 TeV [1209.0753] — 1.07 TeV g̃ mass
GGM (wino NLSP) : γ + lep + E_T,miss — L=4.8 fb⁻¹, 7 TeV [ATLAS-CONF-2012-144] — 619 GeV g̃ mass
GGM (higgsino-bino NLSP) : γ + b + E_T,miss — L=4.8 fb⁻¹, 7 TeV [1211.1167] — 900 GeV g̃ mass
GGM (higgsino NLSP) : Z + jets + E_T,miss — L=5.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-152] — 690 GeV g̃ mass
Gravitino LSP : 'monojet' + E_T,miss — L=10.5 fb⁻¹, 8 TeV [ATLAS-CONF-2012-147] — 645 GeV F^1/2 scale
g̃→bb̄χ̃⁰ : 0 lep + 3 b-j's + E_T,miss — L=12.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-145] — 1.24 TeV g̃ mass
g̃→tt̄χ̃⁰ : 2 SS-lep + (0-3b-)j's + E_T,miss — L=20.7 fb⁻¹, 8 TeV [ATLAS-CONF-2013-007] — 900 GeV g̃ mass
g̃→tt̄χ̃⁰ : 0 lep + multi-j's + E_T,miss — L=5.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-103] — 1.00 TeV g̃ mass
g̃→tt̄χ̃⁰ : 0 lep + 3 b-j's + E_T,miss — L=12.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-145] — 1.15 TeV g̃ mass
b̃b̃, b̃→bχ̃⁰ : 0 lep + 2-b-jets + E_T,miss — L=12.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-165] — 620 GeV b̃ mass
b̃b̃, b̃→tχ̃± : 2 SS-lep + (0-3b-)j's + E_T,miss — L=20.7 fb⁻¹, 8 TeV [ATLAS-CONF-2013-007] — 430 GeV b̃ mass
t̃t̃ (light), t̃→bχ̃± : 1/2 lep (+ b-jet) + E_T,miss — L=4.7 fb⁻¹, 7 TeV [1208.4305, 1209.2102] — 167 GeV t̃ mass
t̃t̃ (medium), t̃→bχ̃± : 1 lep + b-jet + E_T,miss — L=20.7 fb⁻¹, 8 TeV [ATLAS-CONF-2013-037] — 160-410 GeV t̃ mass
t̃t̃ (medium), t̃→bχ̃± : 2 lep + E_T,miss — L=13.0 fb⁻¹, 8 TeV [ATLAS-CONF-2012-167] — 160-440 GeV t̃ mass
t̃t̃ (heavy), t̃→tχ̃⁰ : 1 lep + b-jet + E_T,miss — L=20.7 fb⁻¹, 8 TeV [ATLAS-CONF-2013-037] — 200-610 GeV t̃ mass
t̃t̃ (heavy), t̃→tχ̃⁰ : 0 lep + 6(2b-)jets + E_T,miss — L=20.5 fb⁻¹, 8 TeV [ATLAS-CONF-2013-024] — 320-660 GeV t̃ mass
t̃t̃ (natural GMSB) : Z(→ll) + b-jet + E_T,miss — L=20.7 fb⁻¹, 8 TeV [ATLAS-CONF-2013-025] — 500 GeV t̃ mass
t̃₂t̃₂, t̃₂→t̃₁+Z : Z(→ll) + 1 lep + b-jet + E_T,miss — L=20.7 fb⁻¹, 8 TeV [ATLAS-CONF-2013-025] — 520 GeV t̃₂ mass
l̃l̃, l̃→lχ̃⁰ : 2 lep + E_T,miss — L=4.7 fb⁻¹, 7 TeV [1208.2884] — 85-195 GeV l̃ mass
χ̃⁺χ̃⁻, χ̃⁺→l̃ν(lν̃) : 2 lep + E_T,miss — L=4.7 fb⁻¹, 7 TeV [1208.2884] — 110-340 GeV χ̃± mass
χ̃⁺χ̃⁻, χ̃⁺→τ̃ν(τν̃) : 2 τ + E_T,miss — L=20.7 fb⁻¹, 8 TeV [ATLAS-CONF-2013-028] — 180-330 GeV χ̃± mass
χ̃±χ̃⁰ → l̃νl̃l(ν̃ν), lν̃l̃l(ν̃ν) : 3 lep + E_T,miss — L=20.7 fb⁻¹, 8 TeV [ATLAS-CONF-2013-035] — 600 GeV χ̃± mass
χ̃±χ̃⁰ → W(*)χ̃⁰Z(*)χ̃⁰ : 3 lep + E_T,miss — L=20.7 fb⁻¹, 8 TeV [ATLAS-CONF-2013-035] — 315 GeV χ̃± mass
Direct χ̃± pair prod. (AMSB) : long-lived χ̃± — L=4.7 fb⁻¹, 7 TeV [1210.2852] — 220 GeV χ̃± mass
Stable g̃, R-hadrons : low β, βγ — L=4.7 fb⁻¹, 7 TeV [1211.1597] — 985 GeV g̃ mass
GMSB, stable τ̃ : low β — L=4.7 fb⁻¹, 7 TeV [1211.1597] — 300 GeV τ̃ mass
GMSB, χ̃⁰→γG̃ : non-pointing photons — L=4.7 fb⁻¹, 7 TeV [ATLAS-CONF-2013-016] — 230 GeV χ̃⁰ mass
χ̃⁰ → qqμ (RPV) : μ + heavy displaced vertex — L=4.4 fb⁻¹, 7 TeV [1210.7451] — 700 GeV q̃ mass
LFV : pp→ν̃τ+X, ν̃τ→e+μ resonance — L=4.6 fb⁻¹, 7 TeV [1212.1272] — 1.61 TeV ν̃τ mass
LFV : pp→ν̃τ+X, ν̃τ→e(μ)+τ resonance — L=4.6 fb⁻¹, 7 TeV [1212.1272] — 1.10 TeV ν̃τ mass
Bilinear RPV CMSSM : 1 lep + 7 j's + E_T,miss — L=4.7 fb⁻¹, 7 TeV [ATLAS-CONF-2012-140] — 1.2 TeV q̃ = g̃ mass
χ̃⁺χ̃⁻, χ̃⁺→Wχ̃⁰, χ̃⁰→eeν, eμν : 4 lep + E_T,miss — L=20.7 fb⁻¹, 8 TeV [ATLAS-CONF-2013-036] — 760 GeV χ̃± mass
χ̃⁺χ̃⁻, ..., χ̃⁰→ττν, eτν : 3 lep + 1τ + E_T,miss — L=20.7 fb⁻¹, 8 TeV [ATLAS-CONF-2013-036] — 350 GeV χ̃± mass
g̃ → qqq : 3-jet resonance pair — L=4.6 fb⁻¹, 7 TeV [1210.4813] — 666 GeV g̃ mass
g̃→t̃t, t̃→bs : 2 SS-lep + (0-3b-)j's + E_T,miss — L=20.7 fb⁻¹, 8 TeV [ATLAS-CONF-2013-007] — 880 GeV g̃ mass
Scalar gluon : 2-jet resonance pair — L=4.6 fb⁻¹, 7 TeV [1210.4826] — 100-287 GeV sgluon mass
WIMP interaction (D5, Dirac χ) : 'monojet' + E_T,miss — L=10.5 fb⁻¹, 8 TeV [ATLAS-CONF-2012-147] — 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 ~ 126 GeV

- consistent with expectation from precision tests of the SM
- favors perturbative physics   quartic coupling $\lambda = m_H^2/v^2 \simeq 1/8$
- 1st elementary scalar in nature signaling perhaps more to come

Window to new physics ?

- compatible with supersymmetry

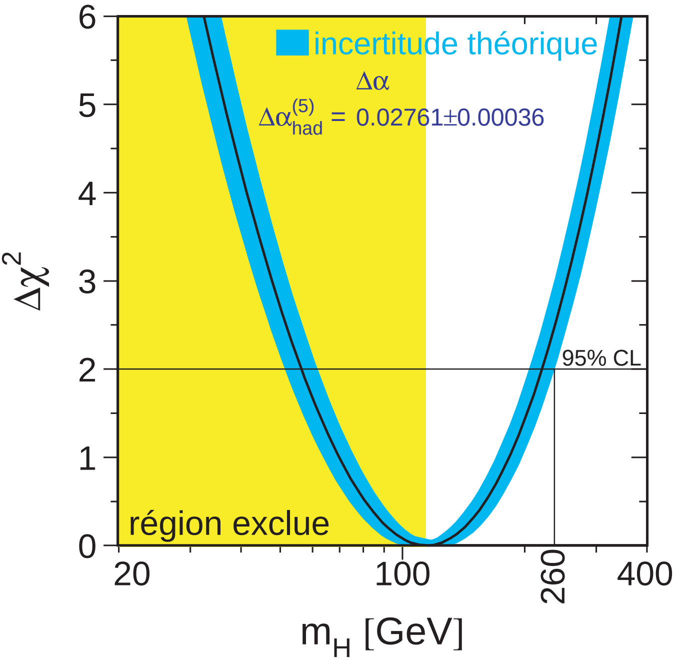
  but appears fine-tuned in its minimal version [10]

  early to draw a general conclusion before LHC13/14 [11]

  e.g. an extra singlet or split families can alleviate the fine tuning [12]
- very important to measure its properties and couplings

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

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


incertitude théorique
Δα
$\Delta\alpha^{(5)}_{had} = 0.02761 \pm 0.00036$
95% CL
région exclue
6
5
4
3
2
1
0
$\Delta\chi^2$
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 $A_t \simeq 3m_{\tilde{t}} \simeq 1.5$ 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: $m_2^2 = m_2^2(M_{\mathrm{GUT}}) - \dfrac{3\lambda_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln\dfrac{M_{\mathrm{GUT}}}{m_{\tilde{t}}} + \cdots$ [20]

$$\sim m_2^2(M_{\mathrm{GUT}}) - \mathcal{O}(1) m_{\tilde{t}}^2 + \cdots$$ [8]

Reduce the fine-tuning

- minimize radiative corrections

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

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

- extend the MSSM

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

- $\cdots$

MSSM with dim-5 and 6 operators

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

parametrize new physics above MSSM by higher-dim effective operators

relevant super potential operators of dimension-5:

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

η_1 : generated for instance by a singlet

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

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

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

Physical consequences of MSSM$_5$: Scalar potential

$$\mathcal{V} = m_1^2|h_1|^2 + m_2^2|h_2|^2 + B\mu(h_1h_2 + \mathrm{h.c.}) + \frac{g_2^2+g_Y^2}{8}\left(|h_1|^2 - |h_2|^2\right)^2$$
$$+ \left(|h_1|^2 + |h_2|^2\right)(\eta_1 h_1 h_2 + \mathrm{h.c.}) + \frac{1}{2}\left[\eta_2 (h_1h_2)^2 + \mathrm{h.c.}\right]$$
$$+ \eta_1^2\,|h_1h_2|^2\left(|h_1|^2 + |h_2|^2\right)$$

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

  Bernal-Blum-Nir-Losada '09
- last term $\sim \eta_1^2$: guarantees stability of the potential

  but requires addition of dim-6 operators

MSSM Higss with dim-6 operators

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

Classification of all dim-6 contributing to the scalar potential

(without $\not{\text{S}}$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

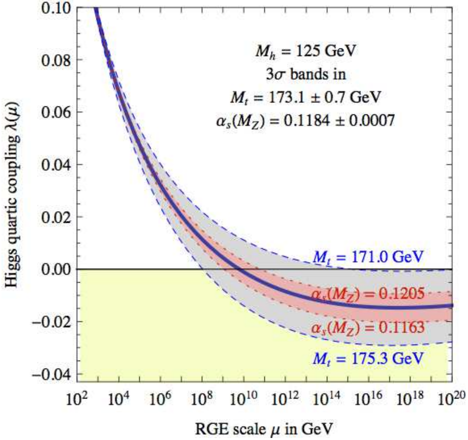
$\Rightarrow m_h \simeq 103 - 119$ GeV

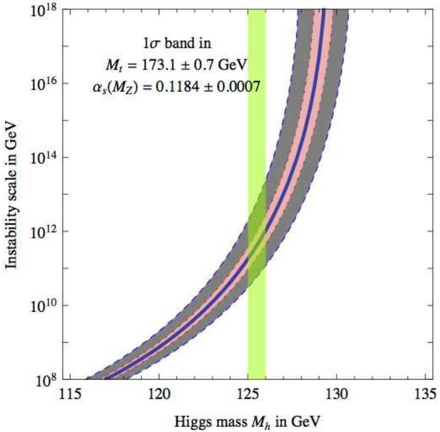
$\Rightarrow$ MSSM with dim-5 and dim-6 operators:

possible resolution of the MSSM fine-tuning problem

Can the SM be valid at high energies?

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





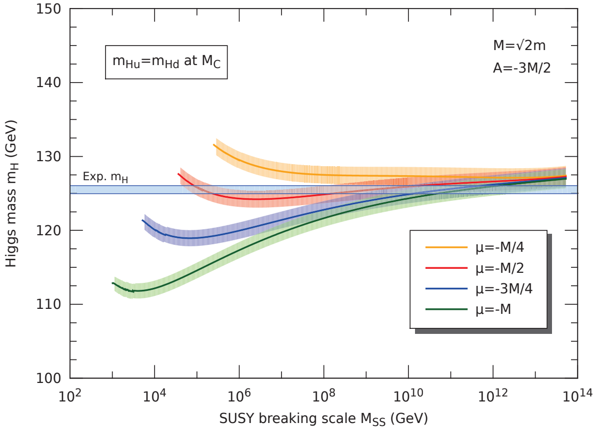
Instability of the SM Higgs potential $\Rightarrow$ metastability of the EW vacuum

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

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

$\lambda = 0$ 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 $\Rightarrow$ 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 [20]

  $m_S \sim$ few - thousands TeV

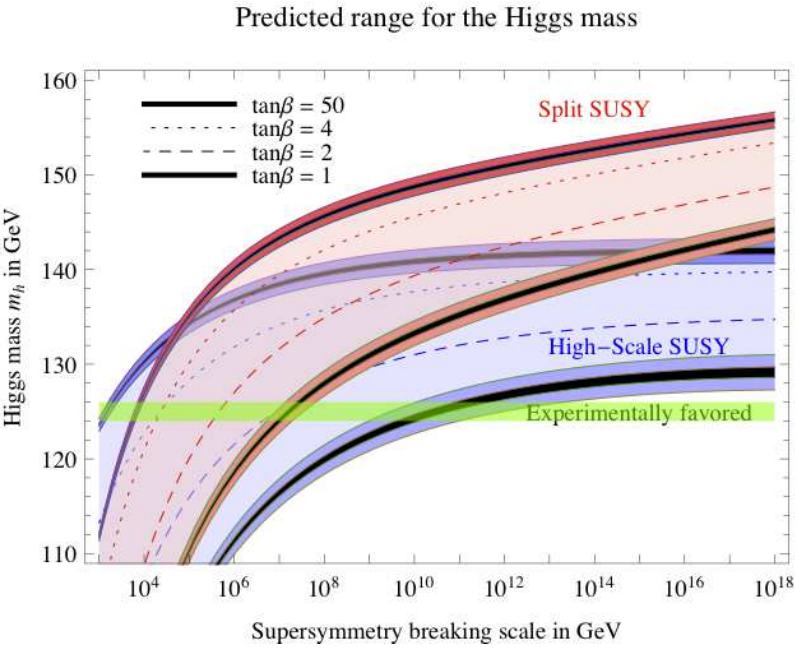
  gauginos: a loop factor lighter than scalars ($\sim m_{3/2}$)
- natural string framework: intersecting (or magnetized) branes

  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: $B, L, \dots$

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

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

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

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

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

$M_s \sim 1$ TeV $\Rrightarrow$ 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 [10]

$\Lambda \sim$ 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

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 [23]

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

  higher spin excitations of quarks and gluons with strong interactions

  present LHC limits: $M_s \gtrsim 5$ TeV

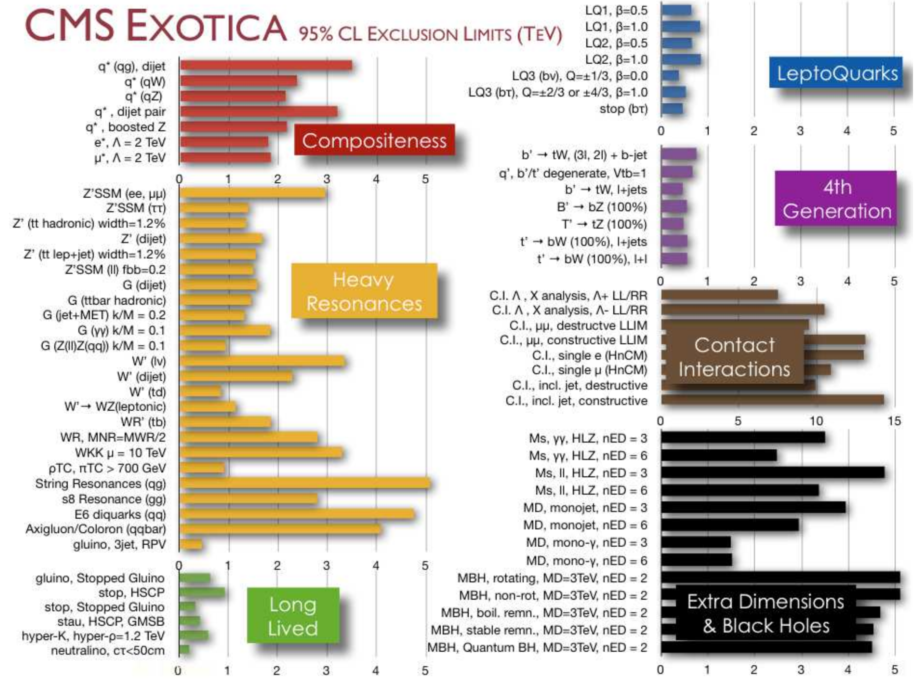
- Large TeV dimensions $\Rightarrow$ KK resonances of SM gauge bosons I.A. '90

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

  experimental limits: $R^{-1} \gtrsim 0.5 - 4$ TeV (UED - localized fermions) [25]

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

  masses suppressed by a loop factor from M_s [27]

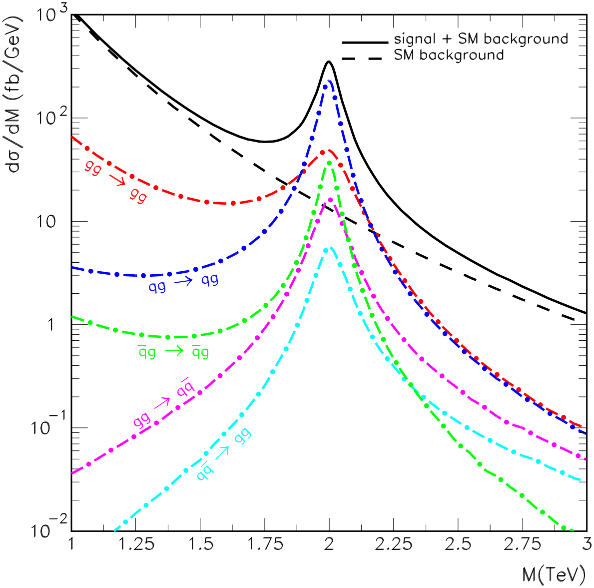

CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)
Compositeness
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
Heavy Resonances
Z'SSM (ee, μμ)
Z'SSM (ττ)
Z' (tt hadronic) width=1.2%
Z' (dijet)
Z' (tt lep+jet) width=1.2%
Z'SSM (ll) fbb=0.2
G (dijet)
G (ttbar hadronic)
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
Long Lived
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
neutralino, cτ<50cm
LeptoQuarks
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)
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
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
Extra Dimensions & Black Holes
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
0 1 2 3 4 5
0 5 10 15

Universal deviation from Standard Model in jet distribution

$M_s = 2$ TeV

Width $=$ 15-150 GeV

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



Tree level superstring amplitudes involving at most 2 fermions and gluons:

model independent for any compactification, # of susy's, even none

no intermediate exchange of KK, windings or graviton emmission

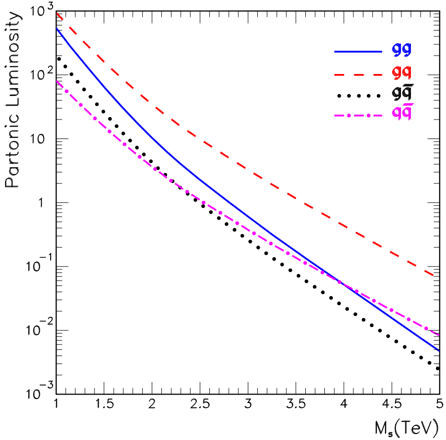
Universal sum over infinite exchange of string (Regge) excitations

Parton luminosities in pp above TeV

are dominated by *gq*, *gg*

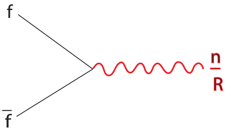
$\Rightarrow$ model independent

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



Localized fermions (on 3-brane intersections)

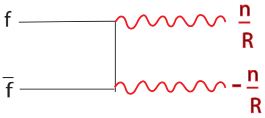
$\Rightarrow$ single production of KK modes I.A.-Benakli '94



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

Otherwise KK momentum conservation

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



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

Servant-Tait '02

UED hadron collider phenomenology

- large rates for KK-quark and KK-gluon production
- cascade decays via KK-W bosons and KK-leptons

  determine particle properties from different distributions

- missing energy from LKP: weakly interacting escaping detection
- phenomenology similar to supersymmetry

  spin determination important for distinguishing SUSY and UED [21]

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

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

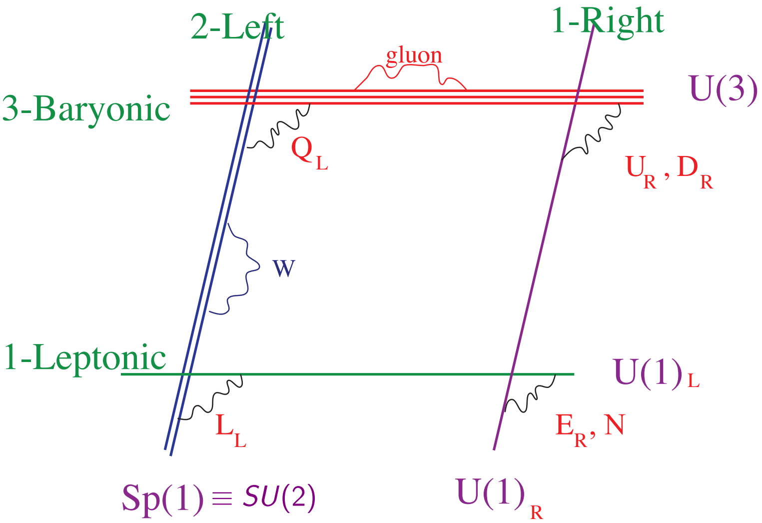
- 4d anomalous $U(1)$'s: $M_A \simeq g_A M_s$

- 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

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



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

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

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		