Mass hierarchy and physics beyond the Standard Theory

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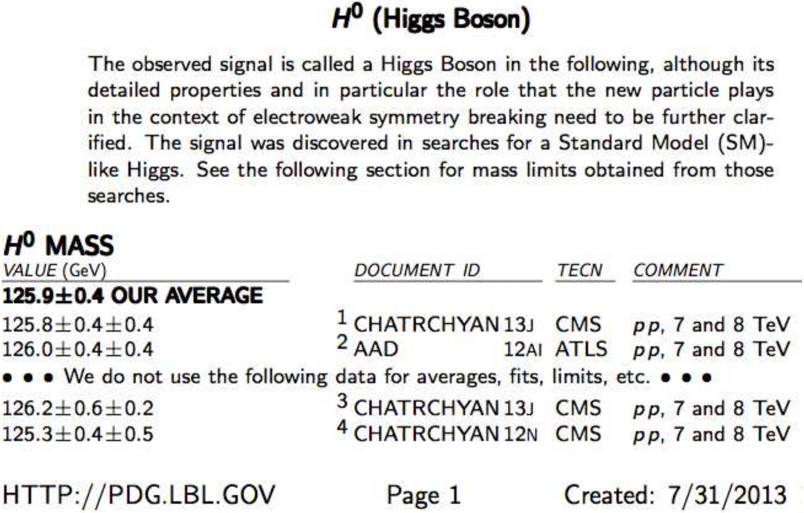
PASCOS 2013

Taipei Taiwan, 20-26 November 2013

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

Entrance of the Higgs Boson in the Particle Data Group 2013

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

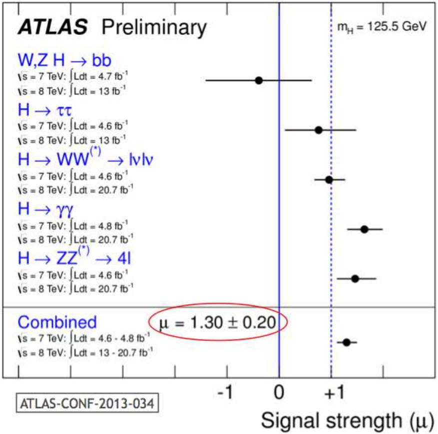
summary tables

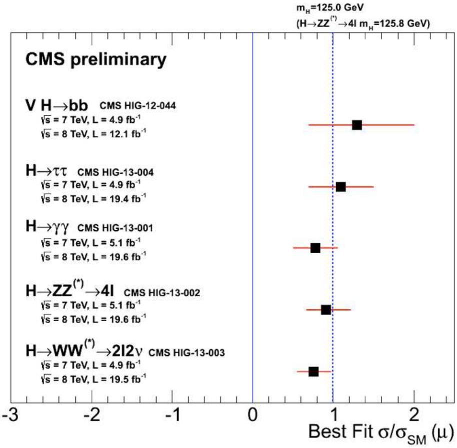
H^0 Mass $m = 125.9 \pm 0.4$ GeV

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 ± 0.33
$b\bar{b}$ Final State = $0.5^{+0.8}_{-0.7}$
$\tau^+\tau^-$ Final State = 0.1 ± 0.7

Couplings of the new boson vs SM





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

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

François Englert ↓ Peter Higgs ↓

Nobel Prize of Physics 2013

Remarks on the value of the Higgs mass ~ 126 GeV

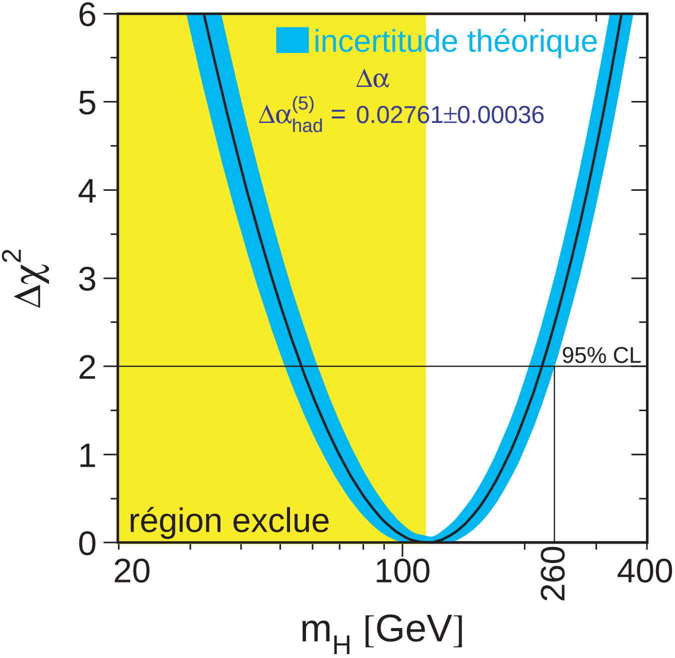
- consistent with expectation from precision tests of the SM
- favors perturbative physics quartic coupling $\lambda = m_H^2/v^2 \simeq 1/8$
- 1st elementary scalar in nature signaling perhaps more to come
- triumph of QFT and renormalized perturbation theory!

  Standard Theory has been tested with radiative corrections

Window to new physics ?

- very important to measure precisely its properties and couplings
- several new and old questions wait for answers

  Dark matter, neutrino masses, baryon asymmetry, flavor physics, axions, electroweak scale hierarchy, early cosmology, ...



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]

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

Standard picture: low energy supersymmetry

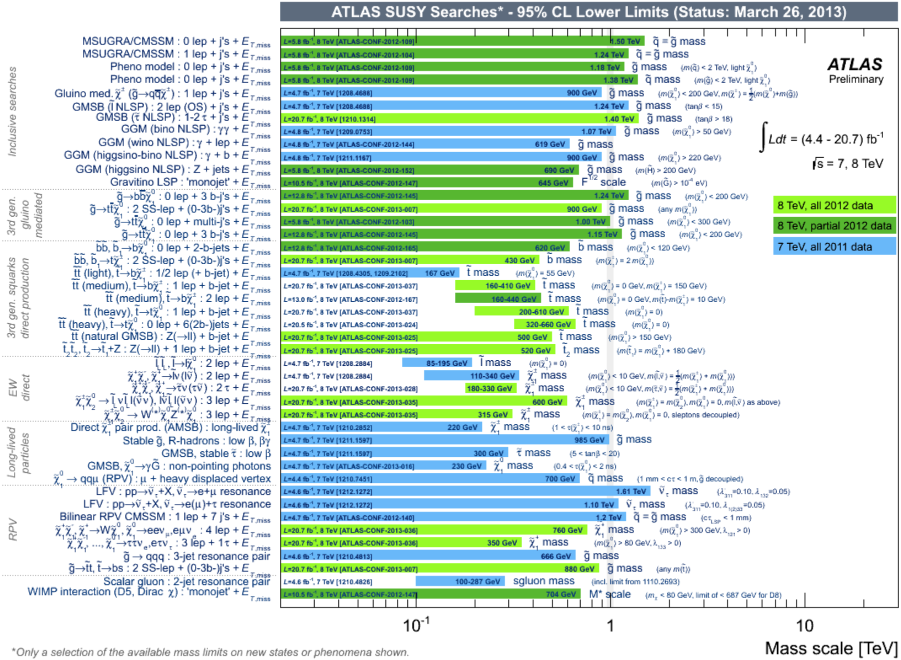
Natural framework: Heterotic string (or high-scale M/F) theory

Advantages:

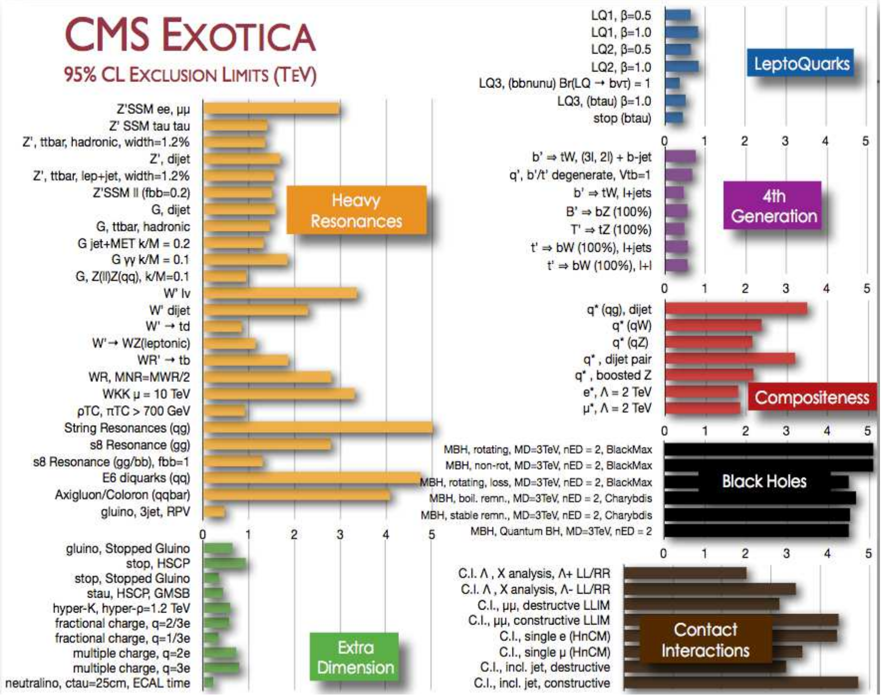
- natural elementary scalars
- gauge coupling unification
- LSP: natural dark matter candidate
- radiative EWSB

Problems:

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



*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

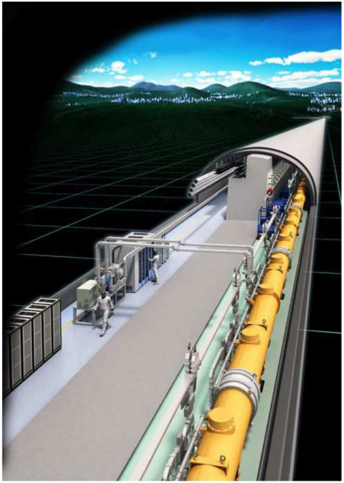
What to do?

Physics is an experimental science

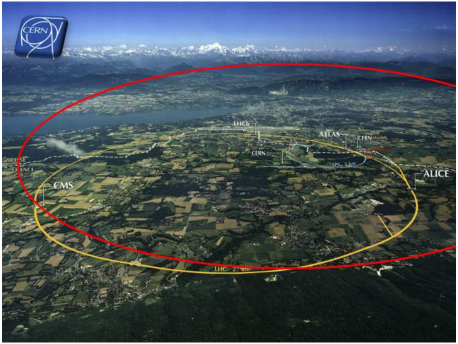
- Exploit the full potential of LHC
- Go on and fully explore the multi TeV energy range

We must fully explore the 10-100 TeV energy range

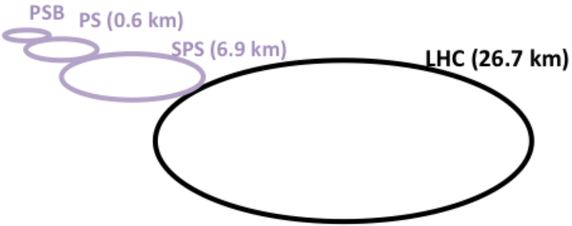
ILC project



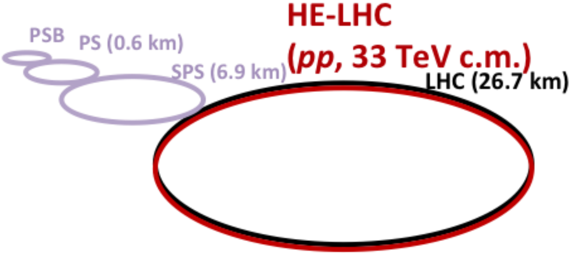
The future of LHC



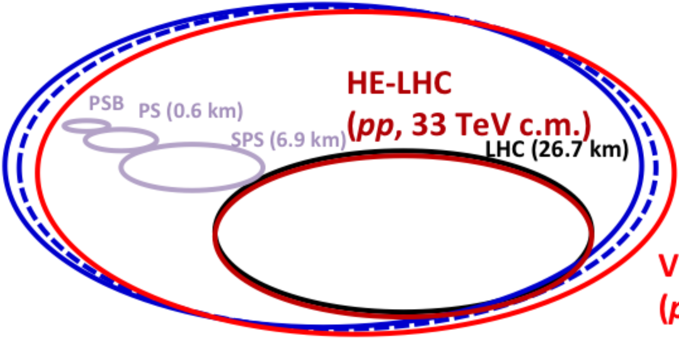
possible long-term strategy



possible long-term strategy



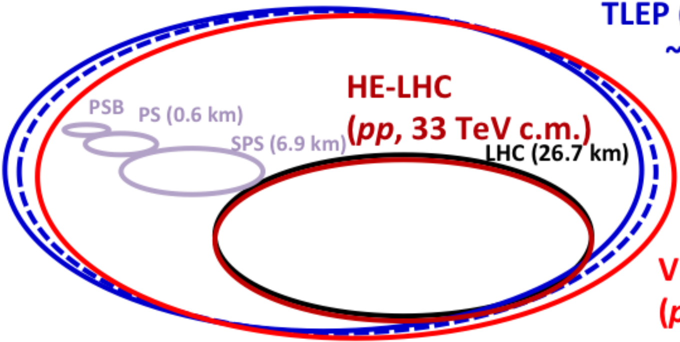
possible long-term strategy



HE-LHC
(*pp*, 33 TeV c.m.)

VHE-LHC
(*pp*, up to
100 TeV c.m.)
same detectors!

possible long-term strategy



TLEP (*e^+e^-* up to ~350 GeV c.m.)

HE-LHC (*pp*, 33 TeV c.m.)

VHE-LHC (*pp*, up to 100 TeV c.m.) same detectors!

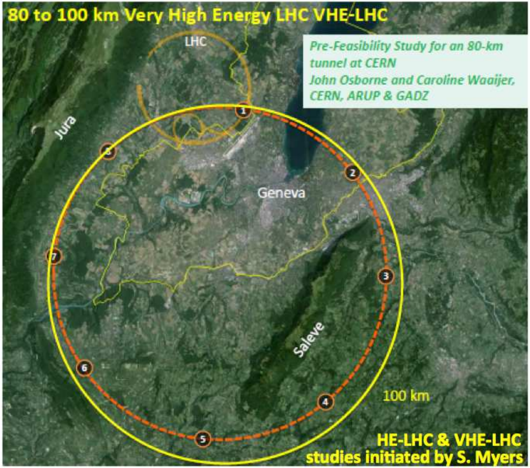
also: ***$e^\pm$* (120 GeV) – *p* (7 & 50 TeV)** collisions

≥50 years of *e^+e^-*, *pp*, *ep/A* physics at highest energies

VHE-LHC: location and size

- 100 TeV p-p collider
- CDR and cost review to be ready for next European Strategy Update
- The tunnel could also house a e^+- e^- Higgs factory (TLEP)

	TLEP
circumference	80 km
Beam energy up to	370 GeV c.m.
max no. of IPs	4
Luminosity/IP at 350 GeV c.m.	1.3×10^{34} cm^{-2}s^{-1}
Luminosity/IP at 240 GeV c.m.	4.8×10^{34} cm^{-2}s^{-1}
Luminosity/IP at 160 GeV c.m.	1.6×10^{35} cm^{-2}s^{-1}
Luminosity/IP at 90 GeV c.m.	$5.6\ 10^{35}$ cm^{-2}s^{-1}



80 to 100 km Very High Energy LHC VHE-LHC

Pre-Feasibility Study for an 80-km tunnel at CERN
John Osborne and Caroline Waaijer, CERN, ARUP & GADZ

HE-LHC & VHE-LHC studies initiated by S. Myers

A circumference of 100 km is being considered for cost-benefit reasons

20T magnet in 80 km / 16T magnet in 100 km → 100 TeV

126 GeV Higgs and SUSY

- compatible with supersymmetry (even with MSSM)

  although it appears fine-tuned in its minimal version

  but early to draw a general conclusion before LHC13/14

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

RG evolution: $m_2^2 = \; m_2^2(M_{\rm GUT}) - \frac{3\lambda_t^2}{4\pi^2} m_{\tilde t}^2 \ln\frac{M_{\rm GUT}}{m_{\tilde t}} + \cdots$ [28]

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

Reduce the fine-tuning

- minimize radiative corrections

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

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

- increase the tree-level upper bound ⇛ extend the MSSM

  extra fields beyond LHC reach → 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

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

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

Dine-Seiberg-Thomas '07

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

Physical consequences of MSSM$_5$: Scalar potential

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

- $\eta_{1,2} \Rightarrow$ 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 $\text{SU}\not{\text{S}}\text{Y}$) ⇒

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

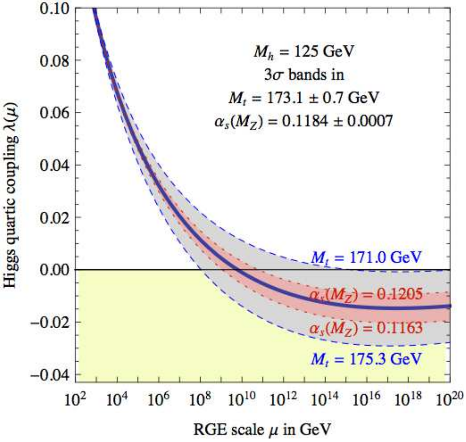
$\Rightarrow m_h \simeq 103 - 119$ GeV

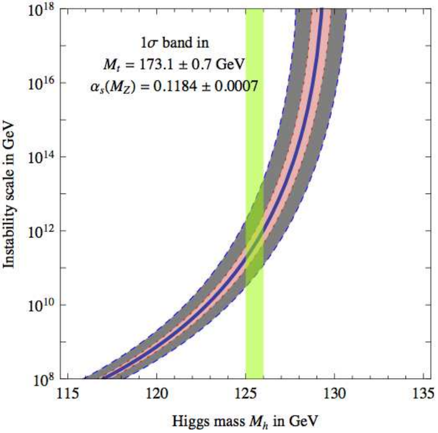
⇒ MSSM with dim-5 and dim-6 operators:

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





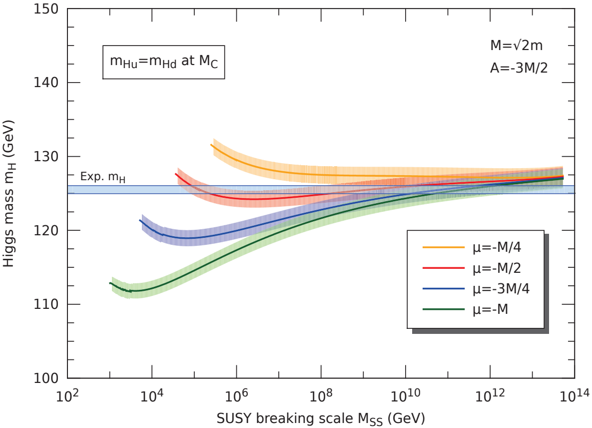
Instability of the SM Higgs potential ⇒ metastability of the EW vacuum

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 ⇛ 'mini' split [28]

  $m_S \sim$ 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

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 $\Rightarrow 0.5 \lesssim g_{U(1)_R} \lesssim 1$
- 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 [19]

$\Lambda \sim$ 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

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

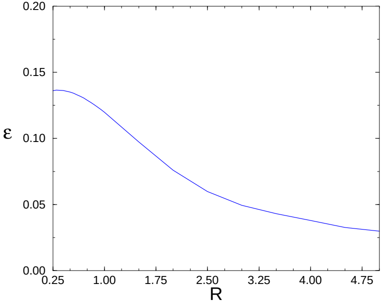
$\mu^2 = 0$ at tree but becomes < 0 at one loop non-susy vacuum

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

$$\varepsilon^2(R) = \frac{R^3}{2\pi^2} \underset{\text{IR}\nearrow}{\overset{\text{UV}\searrow}{\int_0^\infty}} dl\, l^{3/2} \underset{\searrow 1}{\overset{\nearrow e^{-\pi l}}{\frac{\theta_2^4}{16 l^4 \eta^{12}}}} \left(il + \frac{1}{2} \right) \sum_n n^2 e^{-2\pi n^2 R^2 l}$$



$R \to 0$: $\varepsilon(R) \simeq 0.14$ 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

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

  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

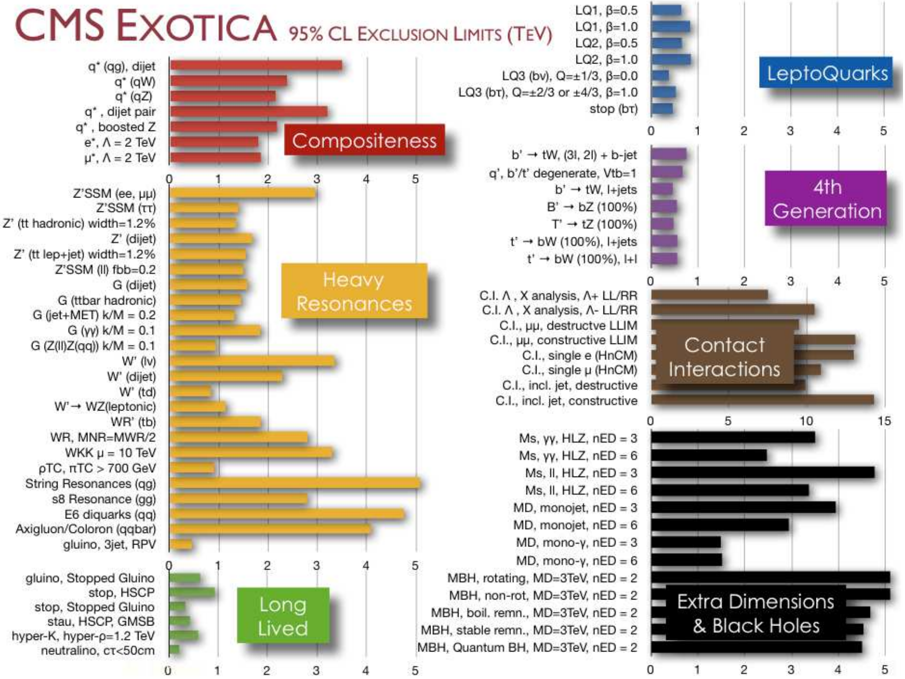
  $$M_k^2 = M_0^2 + k^2/R^2 \ ; \ k = \pm 1, \pm 2, \ldots$$

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

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

  masses suppressed by a loop factor from M_s [33]

CMS EXOTICA 95% CL EXCLUSION LIMITS (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

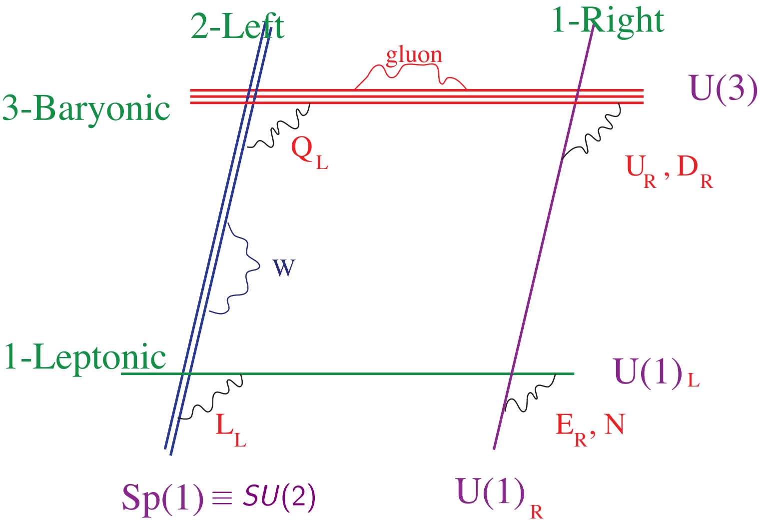
Two kinds of massive $U(1)$'s: I.A.-Kiritsis-Rizos '02

- 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 : 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 $\Rightarrow$ proton stability

  - Lepton number $\Rightarrow$ protect small neutrino masses

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

  $\nwarrow \sim$ 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?

  all options are still open

- LHC enters a new era with possible new discoveries
- Future plans to explore the 10-100 TeV energy frontier

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