Mass hierarchy and physics beyond the Standard Theory

I. Antoniadis

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
**$H^0$ (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**

<table>
<thead>
<tr>
<th>VALUE (GeV)</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>125.9 ± 0.4 OUR AVERAGE</td>
<td>1 CHATRCHYAN 13J</td>
<td>CMS</td>
<td>$p p$, 7 and 8 TeV</td>
</tr>
<tr>
<td>125.8 ± 0.4 ± 0.4</td>
<td>2 AAD 12Al</td>
<td>ATLS</td>
<td>$p p$, 7 and 8 TeV</td>
</tr>
<tr>
<td>126.0 ± 0.4 ± 0.4</td>
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<tr>
<td>• • • We do not use the following data for averages, fits, limits, etc. • • •</td>
<td>3 CHATRCHYAN 13J</td>
<td>CMS</td>
<td>$p p$, 7 and 8 TeV</td>
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<tr>
<td>126.2 ± 0.6 ± 0.2</td>
<td>4 CHATRCHYAN 12N</td>
<td>CMS</td>
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<tr>
<td>125.3 ± 0.4 ± 0.5</td>
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Page 1

Created: 7/31/2013
$H^0$ Mass $m = 125.9 \pm 0.4$ GeV

$H^0$ signal strengths in different channels $[n]$

Combined Final States $= 1.07 \pm 0.26 \quad (S = 1.4)$

$W W^* $ Final State $= 0.88 \pm 0.33 \quad (S = 1.1)$

$Z Z^* $ 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 $\sim 2\sigma$
Remarks on the value of the Higgs mass $\sim 126 \text{ GeV}$

- consistent with expectation from precision tests of the SM
- favors perturbative physics $\text{quartic coupling } \lambda = \frac{m_H^2}{v^2} \approx 1/8$
- 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, . . .
\[ \Delta \alpha^{(5)} = 0.02761 \pm 0.00036 \]

**région exclue**

**95% CL**
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
ATLAS SUSY Searches* - 95% CL Lower Limits (Status: March 26, 2013)

**I. Antoniadis (CERN)**

<table>
<thead>
<tr>
<th>Mass [TeV]</th>
<th>q̃ = g̃ mass</th>
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<td>1.64 TeV</td>
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<td>0.17 TeV</td>
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</tbody>
</table>

**Inclusive searches**

**MSUGRA/CMSSM**
- 0 lep + j' + E_{T,miss} + E_{T,miss}
- 1 lep + j' + E_{T,miss} + E_{T,miss}
- 2 lep + j' + E_{T,miss} + E_{T,miss}

**GMSB (NSLSP)**
- 0 lep + j' + E_{T,miss} + E_{T,miss}
- 1 lep + j' + E_{T,miss} + E_{T,miss}
- 2 lep + j' + E_{T,miss} + E_{T,miss}

**GGM (NLSP)**
- 0 lep + j' + E_{T,miss} + E_{T,miss}
- 1 lep + j' + E_{T,miss} + E_{T,miss}
- 2 lep + j' + E_{T,miss} + E_{T,miss}

**Gravitino LSP**
- 0 lep + j' + E_{T,miss} + E_{T,miss}

**3rd gen. squarks, direct production**
- 0 lep + j' + E_{T,miss} + E_{T,miss}
- 1 lep + j' + E_{T,miss} + E_{T,miss}
- 2 lep + j' + E_{T,miss} + E_{T,miss}

**EW direct**
- 0 lep + j' + E_{T,miss} + E_{T,miss}
- 1 lep + j' + E_{T,miss} + E_{T,miss}
- 2 lep + j' + E_{T,miss} + E_{T,miss}

**Long-lived particles**
- 0 lep + j' + E_{T,miss} + E_{T,miss}
- 1 lep + j' + E_{T,miss} + E_{T,miss}
- 2 lep + j' + E_{T,miss} + E_{T,miss}

**WIMP interaction**
- 0 lep + j' + E_{T,miss} + E_{T,miss}
- 1 lep + j' + E_{T,miss} + E_{T,miss}
- 2 lep + j' + E_{T,miss} + E_{T,miss}

**ATLAS Preliminary**

\[
\int \text{d}t \cdot (4.4 - 20.7) \text{ fb}^{-1} \quad \sqrt{s} = 7, 8 \text{ TeV}
\]

**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 1σ theoretical signal cross section uncertainty.*
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
$(pp, 33 \text{ TeV c.m.})$

LHC (26.7 km)

PSB
PS (0.6 km)

SPS (6.9 km)

VHE-LHC
$(pp, \text{ up to 100 TeV c.m.})$
same detectors!
possible long-term strategy

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

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

LHC (26.7 km)

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

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

$\geq 50$ 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)

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

A circumference of 100 km is being considered for cost-benefit reasons
20T magnet in 80 km / 16T magnet in 100 km → 100 TeV
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
Upper bound on the lightest scalar mass:

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

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

\[\Rightarrow \% \text{ to } \% \% \text{ fine-tuning}
\]

minimum of the potential:

\[m_Z^2 = 2 \frac{m_1^2 - m_2^2 \tan^2 \beta}{\tan^2 \beta - 1} \sim -2m_2^2 + \cdots
\]

RG evolution:

\[m^2_2 = m^2_2(M_{\text{GUT}}) - \frac{3\lambda_t^2}{4\pi^2} m^2_t \ln \frac{M_{\text{GUT}}}{m_\tilde{t}} + \cdots \quad [28]
\]

\[\sim m^2_2(M_{\text{GUT}}) - \mathcal{O}(1)m^2_t + \cdots
\]
Reduce the fine-tuning

- minimize radiative corrections

\[ M_{\text{GUT}} \rightarrow \Lambda : \text{low messenger scale (gauge mediation)} \]

\[ \delta m_t^2 = \frac{8\alpha_s}{3\pi} M_3^2 \ln \frac{\Lambda}{M_3} + \cdots \]

- increase the tree-level upper bound ⇒ extend the MSSM
  
  extra fields beyond LHC reach → effective field theory approach

  . . .
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:

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

\( \eta_1 \): 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

\( \eta_2 \): corresponding soft breaking term

spurion \( S \equiv m_S \theta^2 \)
Physical consequences of MSSM$_5$: Scalar potential

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

- $\eta_{1,2} \Rightarrow$ 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
dim-6 operators can have an independent scale from dim-5

Classification of all dim-6 contributing to the scalar potential (without SU/SY)

large tan β expansion: \( \delta_6 m_h^2 = f v^2 + \cdots \)

constant receiving contributions from several operators

\[ f \sim f_0 \times \left( \frac{\mu^2}{M^2}, \frac{m_S^2}{M^2}, \frac{\mu m_S}{M^2}, \frac{v^2}{M^2} \right) \]

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

\[ \Rightarrow m_h \simeq 103 - 119 \text{ GeV} \]

\[ \Rightarrow \text{MSSM with dim-5 and dim-6 operators:} \]

possible resolution of the MSSM fine-tuning problem
Can the SM be valid at high energies?

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Instability of the SM Higgs potential $\Rightarrow$ metastability of the EW vacuum
SUSY: $\lambda = 0 \Rightarrow \tan \beta = 1$

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

$\lambda = 0$ 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 $^{[28]}$

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

- 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

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 $\Lambda \sim \text{TeV}$

- 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 $R^n_\perp = 10^{32} l^n_s$ ($R_\perp \sim .1 - 10^{-13}$ 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]

$\Lambda \sim \text{a few TeV}$ and $m^2_{H} =$ 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

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

\[ \mu^2 = 0 \text{ at tree but becomes } < 0 \text{ at one loop} \quad \text{non-susy vacuum} \]

simplest case: one scalar doublet from the same brane

\[ \Rightarrow \text{tree-level } V \text{ same as susy: } \lambda = \frac{1}{8}(g^2 + \hat{g}'^2) \quad \text{D-terms} \]

\[ \mu^2 = -g^2 \varepsilon^2 M_s^2 \leftrightarrow \text{effective UV cutoff} \]

\[ \varepsilon^2(R) = \frac{R^3}{2\pi^2} \int_0^\infty d\eta^{3/2} \frac{\theta_2^4}{16l^4\eta^{12}} \left( il + \frac{1}{2} \right) \sum_n n^2 e^{-2\pi n^2 R^2 l} \]
\[
R \to 0 : \quad \varepsilon(R) \simeq 0.14 \quad \text{large transverse dim} \quad R_\perp = l_s^2 / R \to \infty
\]

\[
R \to \infty : \quad \varepsilon(R)M_s \sim \varepsilon_\infty / R \quad \varepsilon_\infty \simeq 0.008 \quad \text{UV cutoff: } M_s \to 1 / R
\]

Higgs scalar = component of a higher dimensional gauge field

\[\Rightarrow \varepsilon_\infty \text{ calculable in the effective field theory}\]

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

\[M_s \text{ or } 1 / R \sim \text{a few or several TeV}\]
Accelerator signatures: 4 different scales

- Gravitational radiation in the bulk $\Rightarrow$ missing energy
  
  \[
  \text{present LHC bounds: } M_* \gtrsim 3 - 5 \text{ TeV}
  \]

- 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
  
  \[
  \text{present LHC limits: } M_s \gtrsim 5 \text{ TeV}
  \]

- Large TeV dimensions $\Rightarrow$ KK resonances of SM gauge bosons
  
  I.A. ’90
  
  \[
  M_k^2 = M_0^2 + k^2 / R^2 \quad ; \quad k = \pm 1, \pm 2, \ldots
  \]
  
  experimental limits: $R^{-1} \gtrsim 0.5 - 4 \text{ TeV}$ (UED - localized fermions)

- Extra $U(1)$’s and anomaly induced terms
  
  masses suppressed by a loop factor from $M_s$ [33]
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: $M_A \sim g_A M_s$

- 4d non-anomalous $U(1)$’s: (but masses related to 6d anomalies)

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

or massless in the absence of such anomalies
Standard Model on D-branes: $SM^{++}$

$Sp(1) \equiv SU(2)$

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

$I. Antoniadis (CERN)$
• $B$ 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

  \[ Z' \sim B \text{ lighter than 4d anomaly free } Z'' \sim B - L \]
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

**2009** Start of LHC

Run 1, 7+8 TeV, \(~25\) fb\(^{-1}\) int. lumi

**2013/14** Prepare LHC for design \(E\) & lumi

Collect \(~30\) fb\(^{-1}\) per year at 13/14 TeV

**2018** Phase-1 upgrade ultimate lumi

**~2022** Phase-2 upgrade to HL-LHC

~300 fb\(^{-1}\) per year, run up to \(>3\) ab\(^{-1}\) collected

**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

**2013/14** Prepare LHC for design \(E\) & lumi

Collect \(~30\) fb\(^{-1}\) per year at 13/14 TeV

**2018** Phase-1 upgrade ultimate lumi

Twice nominal lumi at 14 TeV, \(~100\) fb\(^{-1}\) per year

**~2022** Phase-2 upgrade to HL-LHC

~300 fb\(^{-1}\) per year, run up to \(>3\) ab\(^{-1}\) collected

**LS3** Machine upgrades for high Luminosity

• Upgrade interaction region
• Crab cavities?
• Phase II: full replacement of tracker, new trigger scheme (add L0), readout electronics.

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.