The Higgs boson and new physics

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Outline

• Status of the SM
• Past and present informations on the Higgs boson
• Implications of $M_h \sim 125$ GeV for New Physics vacuum stability, MSSM
• Implication of $\sigma \sim \sigma_{SM}$ for the MSSM
• Conclusions
Present view: The Standard Model

Strong, electromagnetic and weak interactions (not gravity) are described by a renormalizable Quantum Field Theory based on the principle of local gauge invariance with gauge symmetry group $SU(3)_c \times SU(2)_W \times U(1)_Y$ spontaneously broken to $SU(3)_c \times U(1)_{em}$. The quanta of the gauge fields (W,Z) acquire mass via the Higgs mechanism. The left-over of the EWSB process is (at least) a spin 0 particle, the Higgs particle, whose coupling to gauge bosons and to fermions is determined by their masses.

“The Higgs mechanism is just a reincarnation of the Comunist Party: it controls the masses”

Anonymous
\[ \mathcal{L}_{SM} = -\frac{1}{4} F^{a \mu \nu} F_{a \mu \nu} + i \bar{\psi} D \psi + (\lambda_{ij} \bar{\psi}_i \psi_j \phi + h.c) + |D^\mu \phi|^2 - V(\phi) + \bar{N}_i M_{ij} N_j \]

- **Gauge**
  - Symmetry principle
  - Gauge + flavor symmetry

- **Flavor**
  - Renormalizable interactions
  - Principle of minimality
  - Needed to give mass to the particles

- **EWSB**
  - \(\nu\)-mass (Majorana)
  - Neutrinos are special

After spontaneous symmetry breaking the Lagrangian is still renormalizable

Renormalizable lagrangian \(\leftrightarrow\) predictivity at the quantum level
The sector known best: the gauge part
QED (unbroken)

\[ \frac{(g-2)_e}{2} \equiv a_e = a_e^{QED} + a_e^{weak} + a_e^{had} \leq 1 \times 10^{-12} \]

\[ a_{e}^{exp} = 1159652180.73(0.28) \times 10^{-12} \text{ [0.24 ppb]} \]

Hanneke, Fogwell, Gabrielse (08)

\[ a_e^{QED} = \sum_{n=1}^{\infty} \left( \frac{\alpha}{\pi} \right)^n a_e^{(2n)} \quad (n = 5) \]

need \( \alpha \)

\[ \alpha^{-1}(Rb) = 137.035999049(90) \text{ [0.66 ppb]} \]

\[ a_{e}^{th} = 1159652181.78(77) \times 10^{-12} \text{ [0.66 ppb]} \]

\[ a_{e}^{exp} - a_{e}^{th} = -1.05(0.82) \times 10^{-12} \]

best determination of \( \alpha \) is from \( a_e \)

\[ \alpha^{-1}(a_e) = 137.035999173(8)(33) \text{ [0.25 ppb]} \]
\[ a_\mu = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had} \]

sensitivity to hadronic, weak and NP contributions increased in by a factor \((m_\mu/m_e)^2 \sim 4 \cdot 10^4\) with respect to \(a_e\)

\[ a_{\mu}^{exp} = 116\,592\,089(63) \times 10^{-11} \]

\[ a_{\mu}^{th} = 116\,592\,840(59) \times 10^{-11} \]

\[ \Delta a_\mu = a_\mu^{exp} - a_\mu^{th} = 249(87) \times 10^{-11} \]

\[ a_{\mu}^{weak} = 154(2) \times 10^{-11} \]

0.5 parts per million.
Muon g-2 Coll. (06)

\[ \Delta a_\mu \text{ in the ballpark for a NP explanation} \]
The sector known best: the gauge part
Electroweak (broken, W and Z physics)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \alpha^{(5)}_{\text{had}}(m_Z)$</td>
<td>0.02750 ± 0.00033 0.02759</td>
</tr>
<tr>
<td>$m_Z [\text{GeV}]$</td>
<td>91.1875 ± 0.0021  91.1874</td>
</tr>
<tr>
<td>$\Gamma_Z [\text{GeV}]$</td>
<td>2.4952 ± 0.0023  2.4959</td>
</tr>
<tr>
<td>$\sigma^0_{\text{had}} [\text{nb}]$</td>
<td>41.540 ± 0.037  41.478</td>
</tr>
<tr>
<td>$R_l$</td>
<td>20.767 ± 0.025  20.742</td>
</tr>
<tr>
<td>$A^{0,l}_{\text{fb}}$</td>
<td>0.01714 ± 0.00095 0.01645</td>
</tr>
<tr>
<td>$A_l(P_c)$</td>
<td>0.1465 ± 0.0032  0.1481</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.21629 ± 0.00066 0.21579</td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.1721 ± 0.0030  0.1723</td>
</tr>
<tr>
<td>$A^{0,b}_{\text{fb}}$</td>
<td>0.0992 ± 0.0016  0.1038</td>
</tr>
<tr>
<td>$A^{0,c}_{\text{fb}}$</td>
<td>0.0707 ± 0.0035  0.0742</td>
</tr>
<tr>
<td>$A_{b}$</td>
<td>0.923 ± 0.020  0.935</td>
</tr>
<tr>
<td>$A_{c}$</td>
<td>0.670 ± 0.027  0.668</td>
</tr>
<tr>
<td>$A_l(\text{SLD})$</td>
<td>0.1513 ± 0.0021  0.1481</td>
</tr>
<tr>
<td>$\sin^2\theta_{\text{eff}}(Q_{\text{fb}})$</td>
<td>0.2324 ± 0.0012  0.2314</td>
</tr>
<tr>
<td>$m_W [\text{GeV}]$</td>
<td>80.385 ± 0.015  80.377</td>
</tr>
<tr>
<td>$\Gamma_W [\text{GeV}]$</td>
<td>2.085 ± 0.042  2.092</td>
</tr>
<tr>
<td>$m_t [\text{GeV}]$</td>
<td>173.20 ± 0.90  173.26</td>
</tr>
</tbody>
</table>

March 2012

Sensitivity to quantum effects

\[ \sim \alpha \frac{M_t^2}{M_W^2} \]

\[ \sim \alpha \log \frac{M_h^2}{M_Z^2} \]
Purely EW corrections established

indirect vs. direct
$M_t, M_W$ determination

only QED corrections
The Higgs sector: pre-LHC

LEP

Known $M_t, M_W \rightarrow M_h$

\[ Q = \frac{\mathcal{L}(s + b)}{\mathcal{L}(b)} \]
The Higgs sector: pre-LHC
LEP + Tevatron

Combining direct and indirect information:
D'Agostini, G.D. 1999

The consistency of the (minimal) SM at the quantum level predicts a Higgs boson with mass between 110 and 160 GeV

courtesy of S. Di Vita

The consistency of the (minimal) SM at the quantum level predicts a Higgs boson with mass between 110 and 160 GeV
Gluon-fusion process dominant
Weak-boson fusion has a very good-signal/background ratio
Bands include: PDF + $\alpha_s$ + scale uncertainties
Heavy replicas of SM particles contribute to gluon-fusion: ex. 4$^\text{th}$ generation
A NP increase in gluon-fusion X-sect. often corresponds to a decrease of \( \text{BR}(H \rightarrow \gamma\gamma) \).

The \( \text{BR}(H \rightarrow \gamma\gamma) \) can increase if NP reduces the other BR's.

**Golden Channel V=Z**

**Low Higgs mass**

**SM: W - t**

**NP: white + colored**
Clear evidence of a new particle with properties compatible with those of the SM Higgs boson
The Higgs sector: LHC
Study the properties of the new particle

$M_h = 125.5 \pm 0.2(\text{stat}) \pm 0.5(\text{syst})$  GeV

$M_h = 125.8 \pm 0.4(\text{stat}) \pm 0.4(\text{syst})$  GeV
Implications of $M_h \sim 125$ GeV

Well, what did you expect from a particle with no spin?
Reversing the heavy Higgs argument

Specific type of NP could allow a heavy Higgs in the EW fit ("conspiracy"). Take

\[ \hat{\rho} = \rho_0 + \delta \rho (\rho_0^{SM} = 1, \delta \rho \leftrightarrow (\epsilon_1, T)) \]

\[ \Delta \hat{r}_W \leftrightarrow (\epsilon_3, S) \]

\[ \sin^2 \theta_{eff}^{lept} \sim \frac{1}{2} \left\{ 1 - \left[ 1 - \frac{4A^2}{M_Z^2 \hat{\rho} (1 - \Delta \hat{r}_W)} \right]^{1/2} \right\} \]

\[ \sim (\sin^2 \theta_{eff}^{lept})^o + c_1 \ln \left( \frac{M_H}{M_H^o} \right) + c_2 \left[ \frac{(\Delta \alpha)_{\hat{h}}}{(\Delta \alpha)_{\hat{h}}^o} - 1 \right] - c_3 \left[ \left( \frac{M_{\tilde{t}}}{M_{\tilde{t}}^o} \right)^2 - 1 \right] + \ldots \]

\[ c_i > 0 \]

To increase the fitted \( M_H \):

\[ \hat{\rho} > 1 \rightarrow \left\{ \begin{array}{l} \rho_0 > 1 \quad \rightarrow \quad \text{Extra Z} \\ \delta \rho > 0 \quad \rightarrow \quad \text{Isospiltt (s)fermions,} \\ \Delta \hat{r}_W < 0 \quad \rightarrow \quad \text{Multi Higgs models,} \\ \text{Light sleptons} \end{array} \right. \]

NP (if there) seems to be of the decoupling type
Quantum corrections to the classical Higgs potential can modify its shape

\[ V^{\text{class}}(\phi) = -\frac{1}{2}m^2\phi^2 + \lambda\phi^4 \rightarrow V^{\text{eff}} \approx -\frac{1}{2}m^2(\mu)\phi^2(\mu) + \lambda(\mu)\phi^4(\mu) \sim \lambda(\mu)\phi^4(\mu) \]

\[ \phi \sim \mu \gg v \]

\[ \frac{d\lambda}{d\ln \mu} = \frac{1}{16\pi^2} \left[ +24\lambda^2 - 2N_c Y_t + \ldots \right] \]

\( \lambda \) runs

\[ \lambda \quad \lambda^2 \quad \lambda Y^2 \quad \lambda g^2 \quad g^4 \quad Y^4 \]

\( M_H \) large: \( \lambda^2 \) wins

\[ \lambda(M_t) \rightarrow \lambda(\mu) \gg 1 \]

non-perturbative regime, Landau pole

\( M_H \) small: \( -Y_t^4 \) wins

\[ \lambda(M_t) \rightarrow \lambda(\mu) \ll 1 \]
$M_H \sim 125-126$ GeV: $-Y_t^4$ wins
no problem with the Landau pole

Running depends on
$M_T$, $\alpha_s$ ....

$M_H \sim 125-126$ GeV: $-Y_t^4$ wins: $\lambda(M_T) \sim 0.14$ runs towards smaller values and can eventually become negative. If so the potential is either unbounded from below or can develop a second (deeper) minimum at large field values
Illustrative

If your mexican hat turns out to be a dog bowl you have a problem...

from A. Strumia
The problem

There is a transition probability between the false and true vacua

It is really a problem?

It is a problem that must be cured via the appearance of New Physics at a scale below that where the potential become unstable ONLY if the transition probability is smaller than the life of the universe.

Metastability condition: if $\lambda$ becomes negative provided it remains small in absolute magnitude the SM vacuum is unstable but sufficiently long-lived compared to the age of the Universe.
Vacuum stability at NNLO

- Two-loop effective potential (complete)  
  Ford, Jack, Jones 92,97; Martin (02)

- Three-loop beta functions gauge
  Mihaila, Salomon, Steinhauser (12)
  Yukawa, Higgs  
  Chetyrkin, Zoller (12, 13)

- Two-loop threshold corrections at the weak scale
  \[ \lambda: \text{Yuk x QCD} \quad \text{Bezrukov et al. (12)} \]
  \[ \text{Yuk x QCD} \quad \text{Di Vita, Elias-Miro', Espinosa, Giudice} \]
  \[ \text{SM gaugeless} \quad \text{Isidori, Strumia, G.D. (12)} \]

Dominant theory uncertainty on the Higgs mass value that ensures vacuum stability still comes from the residual missing two-loop threshold corrections for \( \lambda \) at the weak scale

\[
\frac{G_\mu}{\sqrt{2}} = \frac{1}{2v_0^2}(1 + \Delta r_0) \\
\lambda(\mu) = \frac{G_\mu}{\sqrt{2}} M_h^2 - \delta \lambda^{(1)} - \delta \lambda^{(2)} \\
\delta \lambda^{(2)} = \frac{G_\mu}{\sqrt{2}} M_h^2 \left\{ \Delta r_0^{(2)} + \frac{1}{M_h^2} \left[ T^{(2)} + \text{Re} \Pi^{(2)}_{hh}(M_h^2) \right] \right. \\
\left. - \frac{\Delta r_0^{(1)}}{M_h^2} \left[ M_h^2 \Delta r_0^{(1)} + \frac{3}{2v_{\text{ren}}} T^{(1)} + \text{Re} \Pi^{(1)}_{hh}(M_h^2) \right] \right\}
\]
Full stability is lost at $\Lambda \sim 10^{11}$ GeV. but $\lambda$ never becomes too negative

$$\lambda(M_{Pl.}) = -0.0144 + 0.0028 \left( \frac{M_h}{\text{GeV}} - 125 \right) \pm 0.0047 M_t \pm 0.0018 \alpha_s(M_Z) \pm 0.0028_{\text{th}}$$

Both $\lambda$ and $\beta_\lambda$ are very close to zero around the Planck mass

Are they vanishing there?
We live in a metastable universe close to the border with the stability region.
If the top pole mass would be $\sim 171$ GeV we were in the stable region.
Is the Tevatron number really the “pole” (what is?) mass?
Monte Carlo are used to reconstruct the top pole mass form its decays products that contain jets, missing energy and initial state radiation.

\[
M_h \text{ [GeV]} > 129.4 + 1.4 \left( \frac{M_t \text{ [GeV]} - 173.1}{0.7} \right) - 0.5 \left( \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0_{th}
\]

$M_t^{\overline{MS}}$ can be extracted from total production cross section and the corresponding pole mass is consistent with the standard value albeit with a larger error.
$M_h \sim 125 \text{ GeV and Supersymmetry}$

Supersymmetry:
- chiral fermion \leftrightarrow complex scalar
- vector boson \leftrightarrow Majorana fermion

$\langle \text{EWSB} \rangle \quad M_P = M_{\tilde{p}}$

In the minimal model the quartic coupling in the Higgs potential is related to the gauge couplings

\[ \rightarrow \text{prediction for the Higgs mass} \]

SUSY must be broken!

It is not possible using SM (super)fields to break SUSY in a realistic way. The breaking of SUSY should come form somewhere else and communicated to the particles we see.

Left-over $L_{\text{SUSY}}^{\text{soft}}$ (may be with some kind of universal features at the scale of the breaking transmission)
The MSSM Higgs sector

Higgs sector:
\[ H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \implies h, H, A, H^\pm \]

Higgs masses: predicted at the tree level in terms of \( M_A, \tan \beta, M_h < M_Z \)

Including radiative corrections: dependence on all SUSY(-breaking) parameters \( (A_t, A_b, \mu \ldots) \)

\[ M_h \lesssim 135 \text{ GeV} \quad \text{decoupling} \quad h \quad \text{SM-like} \]
\[ M_{A,H,H^\pm} \sim 100 \ldots \text{TeV} \]
\[ M_A \sim M_H \sim M_H^\pm > \mathcal{O}(200 \text{GeV}) \]

Large \( \tan \beta \)

<table>
<thead>
<tr>
<th>( \phi )</th>
<th>( g_{u\bar{u}}^\phi )</th>
<th>( g_{d\bar{d}}^\phi )</th>
<th>( g_{VV}^\phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h )</td>
<td>( \cos \alpha / \sin \beta \rightarrow 1 )</td>
<td>( - \sin \alpha / \cos \beta \rightarrow 1 )</td>
<td>( \sin(\beta - \alpha) \rightarrow 1 )</td>
</tr>
<tr>
<td>( H )</td>
<td>( \sin \alpha / \sin \beta \rightarrow 1 / \tan \beta )</td>
<td>( \cos \alpha / \cos \beta \rightarrow \tan \beta )</td>
<td>( \cos(\beta - \alpha) \rightarrow 0 )</td>
</tr>
<tr>
<td>( A )</td>
<td>( 1 / \tan \beta )</td>
<td>( \tan \beta )</td>
<td>( 0 )</td>
</tr>
</tbody>
</table>

delayed decoupling
How easy is to get $M_H \sim 125$ GeV in the MSSM?

$$M_h^2 \simeq M_Z c_{2\beta}^2 + \frac{3 m_t^4}{4 \pi^2 v^2} \left[ \ln \left( \frac{M_S^2}{m_t^2} \right) + \frac{X_t^2}{M_S^2} \left( 1 - \frac{X_t^2}{12 M_S^2} \right) \right] + \ldots$$

SUSY breaking parameters

$$X_t = A_t - \mu \cot \beta, \quad M_S = \sqrt{M_{\tilde{t}_1} M_{\tilde{t}_2}}$$

To get $M_H \sim 125$ GeV:

- Large $\tan \beta$, $\tan \beta > 10$ (increase the tree-level)
- Heavy stops, i.e. large $M_S$ (increase the ln)
- Large stop mixing, i.e. large $X_t$

The more assumptions we take on the mechanism of SUSY-breaking, the more difficult becomes to get $M_H \sim 125$ GeV
pMSSM: minimal assumptions on SUSY-breaking parameters

22 input parameters varying in the domains:

\[ 1 \leq \tan \beta \leq 60, \; 50 \text{ GeV} \leq M_A \leq 3 \text{ TeV}, \; -9 \text{ TeV} \leq A_f \leq 9 \text{ TeV}, \]
\[ 50 \text{ GeV} \leq m_{\tilde{f}_L}, m_{\tilde{f}_R}, M_3 \leq 3 \text{ TeV}, \; 50 \text{ GeV} \leq M_1, M_2, |\mu| \leq 1.5 \text{ TeV}. \]
Costrained scenarios:

(no) GMSB:
\[ \tan \beta, \text{sign}(\mu), M_{\text{mess}}, N_{\text{mess}}, \Lambda \]

(no) AMSB:
\[ \tan \beta, \text{sign}(\mu), m_0, m_{3/2} \]

(Yes) MSUGRA:
\[ \tan \beta, \text{sign}(\mu), m_0, m_{1/2}, A_0 \]

(no) no-scale:
\[ m_0 \approx -A_0 \approx 0 \]

(Yes) VCMSSM:
\[ m_0 \approx A_0 \]

(no) NMSSM:
\[ m_0 \approx 0, \quad A_0 \approx -1/4m_{1/2} \]

(Yes) NUHM:
non universal \[ m_0 \]

Arbey et al., 2011
$M_h \sim 125$ GeV and the SUSY breaking scale

MSSM variant: ($\tilde{m}$: Supersymmetry breaking scale)

High-Scale Supersymmetry

All SUSY particle with mass $\tilde{m}$

Split SUSY:

Susy fermions at the weak scale

Susy scalars with mass $\tilde{m}$

\[
\lambda(\tilde{m}) = \frac{1}{8} \left[ g^2(\tilde{m}) + g'^2(\tilde{m}) \right] \cos^2 2\beta
\]

Supersymmetry broken at a very large scale is disfavored
σ \sim σ_{SM} and the MSSM

Squarks and gluinos contribute to the loop-induced gluon fusion production cross section

\[ \sigma(g g \rightarrow h) \] is fully known at NLO QCD (standard + SUSY contributions)

\[ \sigma(g g \rightarrow h) \] implemented in the event generator POWHEG.

E. Bagnaschi, P. Slavich, A. Vicini, G.D. (11)

a) Interface POWHEG with a mass spectrum generator that provides Higgs masses and couplings.
b) Rescale the SM contribution.
c) Insert the SUSY correction

PO(sitive)W(eight)H(ardest)E(mission)G(enerator)

Nason et al. (04--)

Matching NLO-QCD matrix elements with Parton Showers
Generate the hardest emission first, with NLO accuracy, independently of the PS
Can be interfaces to several SMC programs (HERWIG/PHYTIA)
Generate events with positive weights
NLO accuracy of the total cross-section preserved
\[
\frac{\sigma(gg \to h)}{\sigma(gg \to h_{SM})}
\]

\(m_{Q} = m_{U} = m_{D} = 1000 \text{ GeV, } X_{t} = A_{t} - \mu \cot \beta = 2500 \text{ GeV, } M_{3} = 800 \text{ GeV, } M_{2} = 2 M_{1} = 200 \text{ GeV, } |\mu| = 200 \text{ GeV}\)
\[ \frac{\sigma(g \ g \rightarrow h)}{\sigma(g \ g \rightarrow h_{SM})_{\text{rescaled}}} \]

\[ \mu < 0 \]

\[ \mu > 0 \]

Squarks are heavy: corrections up to 10%
Using the $p_t^h$ to disentangle between SM and MSSM

$\mu < 0$

$\mu > 0$

$R = \frac{d\sigma}{dp_t^h}$ MSSM over SM

obtained using POWHEG + HERWIG

(Bagnaschi et al.)
The ATLAS, CMS plots represent points in the MSSM parameter space different from ours, the SUSY corrections are not included in these plots, but with these limits ……

\[ M_H \sim 125 \text{ GeV: Large } M_A, \text{ to be in the decoupling regime} \]
Light Stops

\[ \frac{\sigma(gg \rightarrow h)}{\sigma(gg \rightarrow h_{SM})} \]

\[ m_Q = m_U = m_D = 500 \text{ GeV}, \ X_t = A_t - \mu \cot \beta = 1250 \text{ GeV}, \ M_3 = 2 M_2 = 4 M_1 = 400 \text{ GeV}, \ |\mu| = 200 \text{ GeV} \]

\[ M_{\tilde{t}_1} \sim 280 \text{ GeV}, \ M_{\tilde{t}_2} \sim 660 \text{ GeV}, \ M_h^{max} < 123 \text{ GeV} \]
For $M_A \sim 200$ GeV squarks corrections are large (30–40%) and genuine SUSY
Conclusions

SM is quite OK

$M_h - 125/6$ GeV is a very intriguing value.

The SM potential is metastable, at the “border” of the stability region. Model-independent conclusion about the scale of NP cannot be derived. $\lambda$ is small at high energy: NP (if exists) should have a *weakly interacting* Higgs particle $\lambda$ and $\beta_\lambda$ are very close to zero around the Planck mass: deep meaning or coincidence?

In the MSSM $M_h - 125/6$ it is at the ”border” of the mass-predicted region. CMSSM models suffer. However, if SUSY exists its scale of breaking cannot be too high.