The Higgs puzzle: experiment and theory

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1. The Standard Model

(The Orthodoxy)
**SM**: renormalizable quantum field theory of strong and electroweak interactions at presently accessible energies

**Missing particle (parameter)**: the Higgs boson $H$ ($m_H$)

The two fundamental roles of the Higgs field in the SM:

- **Spontaneous breaking of the gauge symmetry**
  \[
  \mathcal{L}_S = (D^\mu \phi)^\dagger (D_\mu \phi) - \left[ \mu^2 (\phi^\dagger \phi) + \lambda (\phi^\dagger \phi)^2 \right]
  \]

- **Explicit breaking of the global flavour symmetry**
  \[
  \mathcal{L}_Y = h^U \overline{q}_L u_R \phi + h^D \overline{q}_L d_R \phi + h^E \overline{l}_L e_R \phi + \text{h.c.}
  \]

with increasingly precise tests of both phenomena!

**HIGGS SEARCH** = ultimate, crucial test of the SM

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LEP direct searches for the SM Higgs (⇒ G.Hanson’s talk)

Current LEP-combined results:
(headlines from LHWG/2001-03)

- **Excess** at $2.1\sigma$ over the SM background (Nov.2000 $2.9\sigma$): mainly ALEPH data and four-jet final state

- The maximum likelihood occurs at $m_H = 115.6$ GeV, with $3.5\%$ probability of a SM background fluctuation

- $m_H > 114.1$ GeV at $95\%$ c.l. (115.4 expected)

- 3 out of 4 experiments not yet final
  (final combination ⇒ end 2001)
SM fit to $m_H$ from electroweak precision data

(already discussed in J. Drees’ talk)

LEPEWWG, Summer 2001:
(not including direct searches)

- $m_H = 88^{+53}_{-35}$ GeV
- $m_H < 196$ GeV (95% c.l.)
- $m_H < 222$ GeV (95% c.l.)
- $\chi^2/dof = 22.9/15$ (8.6%)

How does the preference for a light Higgs arise?

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For given values of the remaining SM input parameters precise electroweak data plus theoretical calculations give logarithmic sensitivity to $m_H$, mostly via:

$$\sin^2 \theta_{eff}^{\text{lept}} = (1 - v_l/a_l)/4$$ (asymmetries) and $m_W$

However, there are small theoretical uncertainties, in principle reducible by more refined calculations: complete fermionic 2-loop $m_W$ (Freitas,Hollik,Walter,Weiglein hep-ph/0007091) but other calculations of the same order still missing and, mostly, non-negligible errors in other parameters, e.g.:

$$\Delta \alpha_{had}^{(5)}(m_Z) = \begin{cases} 0.02761 \pm 0.00036 \text{ ‘data driven’} \\ 0.02738 \pm 0.00020 \text{ ‘theory driven’} \end{cases}$$

(Burkhardt, Pietrzyk) (Martin,Outhwaite,Ryszkin)

(plus others, all consistent, e.g.: Jegerlehner $0.02790 \pm 0.00040$ and $0.02773 \pm 0.00021$)

$$m_{\text{top}} = 174.3 \pm 5.1 \text{ GeV}$$
Leptons: \(0.23113 \pm 0.00021\)

Hadrons: \(0.23230 \pm 0.00029\)

\(3.3\sigma\) discrepancy!

\(p\bar{p}\)-colliders: \(80.454 \pm 0.060\)

Average: \(80.451 \pm 0.033\)
Is it all a bed of roses? (Chanowitz, hep-ph/0104024)

- SM fit not great (still OK): $\chi^2/dof = 22.9/15$ (8.6%)
- Small problem with hadronic asymmetries: $2.9\sigma$ pull for $A_{fb}^{0,b}$ in global fit, $s_{eff}(had)$ and $s_{eff}(lep)$ $3.3\sigma$ apart
- Radical modifications of $Zb\bar{b}$ vertex unlikely ($A_b$ from SLD and $R_b$ well behaved)

Exercise: what happens without hadronic asymmetries?

- SM fit improves, $m_H$ pushed down
- Marginal consistency of SM fit with direct limits
  (with significant residual dependence on $\Delta\alpha_{had}^{(5)}(m_Z)$ and $m_{top}$)

A SM crisis lurking around the corner? Wait and see: $m_W$ and $m_t$ at Tevatron, final heavy-flavour LEP analyses
SM = effective theory, $\Lambda =$ scale of new physics
(could be anywhere between TeV and Planck scales)

Very schematically (assuming an elementary SM Higgs):

$$\mathcal{L}_{\text{eff}}^{SM} = \Lambda^4 + \Lambda^2 \phi^2 \quad (\Lambda^{n>0} \Rightarrow \text{hierarchy problems!})$$

$$+ (D\phi)^2 + \overline{\psi} \not{D} \psi + F^{\mu\nu} F_{\mu\nu} + F^{\mu\nu} \tilde{F}_{\mu\nu} + \overline{\psi} \psi \phi + \phi^4$$

(controllable log $\Lambda$ dependence via quantum corrections)

$$+ \frac{\overline{\psi} \psi \phi^2}{\Lambda} + \frac{\overline{\psi} \sigma^{\mu\nu} \psi F_{\mu\nu}}{\Lambda} + \frac{\overline{\psi} \psi \overline{\psi} \psi}{\Lambda^2} + \frac{\phi^2 F^{\mu\nu} F_{\mu\nu}}{\Lambda^2} + \ldots$$

$(\Lambda^{n<0} \Rightarrow \text{rare processes, precision tests, } \bar{B}, \bar{X}, \ldots)$

Can we put firm bounds on the cutoff scale $\Lambda$?
\[ m_H^2 \sim \lambda v^2, \ m_t \sim h_t v \] and the scale of new physics \( \Lambda \)

\[ \frac{d\lambda}{d \log Q} = \frac{3}{16\pi^2} (\lambda^2 + \lambda h_t^2 - h_t^4) + \ldots \]

The triviality bound (given \( m_t \) and \( \Lambda \)):

- \( m_H \) too large \( \Rightarrow \) \( \lambda(Q) \) blows up (Landau pole) at \( Q_0 < \Lambda \)
- \( \Rightarrow \) upper bound on \( m_H \) for any given \( \Lambda \). This leads to the well known constraints (supported by lattice calculations):

\[ m_H < 200 \text{ GeV if } \Lambda \sim M_P \longrightarrow m_H < 600 \text{ GeV if } \Lambda \sim 1 \text{ TeV} \]

The stability bound (given \( m_t \) and \( \Lambda \)):

- \( m_H \) too small \( \Rightarrow \) \( \lambda(Q) \) becomes negative at \( Q_0 < \Lambda \)
- \( \Rightarrow \) another minimum develops at \( \langle \phi \rangle \sim Q_0 \)
- \( \Rightarrow \) lower bound on \( m_H \) for any given \( \Lambda \).
Different options:

1) absolute stability
2) high-$T$ fluctuations
3) $T = 0$ quantum fluctuations

(the most conservative: EW vacuum should live more than $T_U \sim 10^{10}$ yrs)

\[ \Lambda \sim M_P, \ m_H = 115 \text{ GeV}? \]

(1) $\Rightarrow m_t < (166 \pm 2) \text{ GeV}$

(3) $\Rightarrow m_t < (175 \pm 2) \text{ GeV}$

(after new complete 1-loop calculation of tunneling probability at zero temperature)

(there might be reasons to be just at the border [Froggatt,Nielsen,Takanishi hep-ph/0104161])

\[ \alpha_S(m_H) = 0.118 \pm 0.002, \ \Lambda = M_P \]

\[ m_H = 115 \text{ GeV}, \ \alpha_S(m_H) = 0.118 \]

[Isidori,Ridolfi,Strumia hep-ph/0104016]
2. The MSSM

(The Dogma?)
\[ \Lambda^2(\phi^\dagger \phi) \in \mathcal{L}_{\text{eff}}^{SM} : \Lambda \gg \text{TeV} \Rightarrow \text{HIERARCHY PROBLEM} \]

Natural solution: New Physics at the TeV scale

The present best candidate:
Minimal Supersymmetric Standard Model

1. \( \Delta m_{\text{susy}} < \text{TeV} \Rightarrow \Lambda_{\text{MSSM}} = \Lambda_{\text{susy}}^2 / \Delta m_{\text{susy}} \rightarrow \mathcal{O}(M_P) \)
   (in hidden-sector sugra models with \( \Lambda_{\text{susy}} \sim \sqrt{M_{\text{weak}} M_P} \))

2. Generically as good as the SM for EW precision tests
   (SUSY-breaking mass terms do not break \( SU(2) \times U(1) \))

3. For very light sneutrinos (and gauginos), may improve consistency between direct and indirect Higgs bounds
   (when the hadronic asymmetries are left out of the fit)

[Altarelli,Caravaglios,Giudice,Gambino,Ridolfi hep-ph/0104016]
only $m_W$, $\Gamma_l$, $\sin^2_{\text{eff}}(\text{lep})$ and $R_b$ included in the fit

\[ \epsilon_1 = \delta \rho \leftrightarrow m_t, \quad \epsilon_2 \leftrightarrow m_W, \quad \epsilon_3 \leftrightarrow \sin^2_{\text{eff}}(\text{lep}) \]

[Altarelli, Caravaglios, Giudice, Gambino, Ridolfi hep-ph/0104016]
MSSM + desert hypothesis + unification condition \( \Rightarrow \) prediction for the gauge couplings at the weak scale

\[
\frac{d\alpha_A}{d \log Q} = \frac{b_A}{2\pi} \alpha_A^2 + \ldots \quad \text{(one-loop) running coupling constants}
\]

Simple-minded test in terms of \( B = (b_3 - b_2)/(b_2 - b_1) \)

\[
B_{SM} \simeq 0.53 \quad B_{exp} \simeq 0.71 \quad B_{MSSM} \simeq 0.72
\]

(reasonable error estimate: \( \Delta B \sim 0.03 \))

Can such a successful agreement be accidental?

Any other extension of the SM must face this fact!
The MSSM Higgs sector

2 doublets $\Rightarrow$ 5 physical states: $(h, H), A$ and $H^\pm$

SUSY $\Rightarrow$ 2 tree-level parameters, e.g. $(m_A, \tan \beta \equiv v_2/v_1)$

After including loop corrections, dependence on all the MSSM spectrum, in particular on the top-stop parameters

**Status of 2-loop mass calculations** ($p \to 0$ limit):
will become important when $m_t$ more precisely known
(and even more important if/when sparticles found ...)

- **Complete analytical formulae at** $\mathcal{O}(\alpha_t \alpha_s)$
  [Heynemeier, Hollik, Weiglein 1998]  [Degrassi, Slavich, FZ hep-ph/0105096]

- **Partially analytical** $\mathcal{O}(\alpha_t \alpha_s + \alpha_t^2)$ for $m_A \gg m_Z$
  [Espinosa, Zhang 2000] (not yet implemented in experimental codes)

- **Complete analytical formulae at** $\mathcal{O}(\alpha_t \alpha_s + \alpha_t^2)$
  [Brignole, Degrassi, Slavich, FZ 2001 (completed, being checked, agrees with EZ in their limit)]
Effects of the $\mathcal{O}(\alpha_t^2)$ two-loop corrections

\[ M_{h^0} \text{ [GeV]} \]

(a) $M_s = 500 \text{ GeV} \quad \mu = 200 \text{ GeV}$

(b) $M_s = 1 \text{ TeV} \quad \mu = -500 \text{ GeV}$

[Esponosa, Zhang hep-ph/0003246]
MSSM Higgs searches at LEP (⇒ G.Hanson’s talk)

Headlines from LHWG 2001-04: some $\sim 2\sigma$ excesses reported

$e^+e^- \rightarrow hA, hZ$: $(m_h, m_A) \sim (83, 83), (93, 93)$ GeV, $m_h \sim 97, 115$ GeV

Excluded at 95% c.l. (maximal mixing):

$(m_h, m_A) < (91.0, 91.9)$ GeV and $\tan \beta < 2.4$

with typically stronger limits for small stop mixing

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Other recent studies on the MSSM Higgs sector:

- **Tevatron search** for $p\bar{p} \rightarrow b\bar{b}\varphi \rightarrow b\bar{b}b\bar{b}$ ($\varphi = h, H, A$), producing non-trivial constraints for $\tan\beta > 40–50$
  
  [CDF hep-ex/0010052]

- **Radiatively induced CP-violating effects** from explicit phases in the squark-gluino sector, and resulting complications in the discussion of MSSM Higgs searches
  
  [Carena, Ellis, Pilaftsis, Wagner hep-ph/0009212]

- **Implications** of the experimental bounds on MSSM Higgses for models of the ‘mediation’ of SUSY breaking
  
Some weak points of the MSSM

• Incomplete solution of the hierarchy problem
  (scale of soft susy-breaking masses set ‘by hand’)
• Very large number of free parameters
  (no standard model for supersymmetry breaking)
• No experimental hints of Higgs/susy particles
  (in the theoretically most appealing region!)

⇒ must keep an open mind for alternatives
3. Can we do without a light Higgs?

(The Heresy?)
No satisfactory model without a light Higgs
⇒ agnostic point of view: effective theory

1. $SU(2) \times U(1)$ non-linearly realized


$$\mathcal{L}_{\text{eff}} = \frac{v^2}{4} Tr(D_\mu \Sigma D^\mu \Sigma^\dagger) + \sum_i \tilde{c}_i \tilde{O}_i(\Sigma, \tilde{\Lambda}, . . .)$$

$$\Sigma = e^{\frac{2i w^a \tau^a}{v}} D_\mu \Sigma = \partial_\mu \Sigma + i g W^a_\mu \tau^a \Sigma - ig' \Sigma B^3_\mu \tau^3$$

2. $SU(2) \times U(1)$ linearly realized

[Buchmuller, Wyler 1986; . . .; Hall, Kolda 1999; Barbieri, Strumia 1999; Kolda, Murayama 2000]

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}}(\phi) + \sum_i c_i O_i(\phi, \Lambda, . . .)$$

In both approaches:

$$\left( \frac{\sin^2 \theta_{\text{eff}}}{m_W} \right) : \log \frac{m_H}{m_Z} \rightarrow \log \frac{\tilde{\Lambda}(m_H)}{m_Z} + \left( \frac{K_\theta}{K_W} \right)[\tilde{c}_i(c_i)]$$
\((K_\theta, K_W) = \text{unknown coefficients (fundamental theory?)}\)

Present data \(\Rightarrow \tilde{\Lambda}(m_H) \gg m_Z\) without fine-tuning \(K_\theta, W\)

However:

1. **no good candidate theory (so far):** magnitude of \(K_\theta, W\), sign of \(K_\theta, W\), other observables, non ‘ad hoc’, . . .
2. **obvious correlation:** increase \(m_H \Leftrightarrow \text{decrease } \Lambda\)

\(m_H \sim m_Z\) and \(\Lambda \gg m_Z\) most natural solution!

Recent survey of models that may evade \(m_H \sim m_Z\):

(i) **negative** \(S \leftrightarrow \delta \epsilon_3\)

(ii) **new vector bosons** \(Z'\) 

(iii) **positive** \(T \leftrightarrow \delta \epsilon_1\)

all with a rich phenomenology around the TeV scale
4. New theoretical ideas

(Crackpot religions?)
The two big hierarchy problems of our present theories:

\[ \mathcal{L}_{\text{eff}}^{SM} = \Lambda_{\text{cosm}}^4 \left( \text{cosmological constant} \right) + \Lambda_{\text{weak}}^2 \phi^2 \left( \text{gauge hierarchy} \right) \]

with the intriguing numerical relation \( \Lambda_{\text{cosm}} \sim \Lambda_{\text{weak}}^2 / M_P \)

Are the two problems related?

They are in supergravity and superstrings, where breaking SUSY is difficult because both must be addressed at once.

Models formulated in \( D > 4 \) space-time dimensions may offer unconventional solutions and exotic phenomenology.

General aspects discussed in other talks (J.Ellis, L.Randall)

Here just some comments on EW symmetry breaking.
\( \frac{M_{\text{weak}}}{M_P} \) can be linked with some geometrical object (e.g. radius \( R \)), via some model-dependent relation

\[
\frac{M_{\text{weak}}}{M_P} \sim (M_P R)^{-n} , \exp \left[ -k (M_P R) \right] , \ldots
\]

gauge hierarchy problem: understand the stability and the dynamical origin of the value of radius \( R \) that fits \( M_{\text{weak}} \)

[in analogy with \( \Delta m_{\text{susy}} \) in SUSY extensions of the SM]

No compelling idea so far, but some intriguing features

Higher-dimensional field theories are non-renormalizable \( \Rightarrow \) some calculations (e.g. gauge coupling unification) need \( \text{UV completion} \) to make sense (bad cutoff dependence!)
However, if there are symmetries of the higher-dimensional theory whose breaking is non-local in the extra dimensions, symmetry-breaking quantities may be shielded from UV effects and determined by the infrared dynamics. Example:

the field-dependent one-loop effective potential of some compactifications from $d = 5$ to $d = 4$ does not contain positive powers of the cutoff $\Lambda$ (string scale) [Antoniadis 1990]:

$$V_{1-loop}(R, \phi) = R^{-4} + R^{-2}\phi^2 + \phi^4 + \ldots \text{(log corrections)} \ldots$$

Starting from a $d = 5$ theory whose symmetries forbid a Higgs mass term (and ignoring the radius dynamics), $m_H$ and $v = \langle \phi \rangle$ are calculable in terms of $R \Rightarrow 1$ prediction!

One can be more ambitious, and determine dynamically also $R$, if one can compute the coefficient of the $R^{-4}$ term from the gravitational sector of the $d = 5$ theory

[Kounnas, Pavel, FZ 1994]

A promising approach, in rapid development, with several controversial issues that have not been fully settled yet

What features may emerge for Higgs phenomenology? May be too early to tell. One possibility is the mixing between the Higgs and the radions (or sgoldstinos)

[Perazzi, Ridolfi, FZ 2000; Giudice, Rattazzi, Wells 2000; ...]

with possible enhanced couplings of the Higgs to photons, gluons and invisible particles from the gravitational sector

⇒ keep an eye on non-standard Higgs searches
5. The ultimate answer

(The Universal Judgement)
The Tevatron Higgs hunt is on its way!
(as discussed in Y.Y.Kim's talk)

The present:

\[
\sigma(pp \rightarrow VH) \times BR(H \rightarrow bb) \text{ (pb)}
\]

- LEP EXCLUDED
- Standard Model
- CDF PRELIMINARY Run 1
- 95\% C.L. upper limits
- \(ll bb\)
- \(\nu\nu bb\)
- \(qq bb\)
- VH combined

CDF Preliminary Run 1, hep-ex/0106050

slightly smaller sensitivity for D0

The (challenging) future:

\[
m_H < 135 \text{ GeV}: \quad p\bar{p} \rightarrow V + (H \rightarrow bb)
\]

(l\nu)(bb) \quad (l^+l^-)(bb) \quad (\nu\bar{\nu})(bb)

Background: \(Vbb, VV, t\bar{t}, \text{ single top, } \ldots\)

(Tev2 Higgs report, hep-ph/0010338)
SM Higgs searches at the LHC

\[ m_H > 130 \text{ GeV}: \]

\[ H \to ZZ(\ast)[WW(\ast)] \to 4l^{\pm} [\nu\nu], \ldots \]

\[ m_H < 130 \text{ GeV}: \]

- inclusive \( H \to \gamma\gamma \)
- \( t\bar{t} + (H \to b\bar{b}) \)
- \( V + (H \to b\bar{b}) \)
- \( q\bar{q} \to (WW \to H \to WW^{\ast}) + j\ j \)

may be discovery mode for \( m_H \sim 115 \text{ GeV} \)

(Kauer, Plehn, Rainwater, Zeppenfeld hep-ph/0012351)
Other recent studies on SM Higgs at high-energy colliders:

- Soft and virtual NNLO QCD corrections to $gg \rightarrow H + X$

- ‘Strong’ weak effects at high-energies (Bloch-Nordsieck violations): $(\alpha_W/\pi) \log^2(s/m_W^2)$ corrections $\sigma(e^+e^- \rightarrow \text{had})$ and enhanced $m_H$ dependence in $W_L W_L \rightarrow \text{had}$
  (Ciafaloni, Ciafaloni, Comelli hep-th/0103315)

- Higgs + 2 jets via gluon-gluon fusion
  (DelDuca, Kilgore, Oleari, Schmidt, Zeppenfeld hep-th/0105129)

- High-$p_T$ Higgs signals from $WW \rightarrow H \rightarrow b\bar{b}$
  (Khoze, Martin, Ryskin hep-ph/0104230)

- NLO QCD corrections to $p\bar{p}(pp) \rightarrow t\bar{t}H + X$
  (Beenakker, Dittmaier, Krämer, Plumber, Spira, Zerwas hep-ph/0107081)
Conclusions

- Search for ‘Higgs boson’ (dynamics of EW symmetry breaking) main goal of today’s high-energy physics
- Direct searches and EW precision tests strongly constrain the possibilities: light SM(MSSM)-like Higgs looks like the best bet, but still room for the unexpected
- In all ‘natural’ models, the Higgs is not alone: accompanying physics may be even richer in implications, we must be prepared to fully explore the TeV scale
- While not very successful so far, theoretical search for plausible alternatives to MS/MSSM worth pursuing
- The final judgement is coming, experiment will express it: Tevatron-2, the LHC, and hopefully more . . .

There is no substitute for the high-energy frontier!