F. Zwirner
University & INFN, Padova

The Hunt for the Higgs particle

Part 1

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Lecture 1

Preamble

The standard theory of strong, weak and e.m. interactions, effectively coupled to gravity near flat space, describes almost all known physics.

(neutrino oscillations: minor modifications not requiring new physics at the TeV scale)

(some exceptions with gravity and cosmology: dark matter, dark energy, inflation, baryogenesis, …)

Its only part still under discussion: the electroweak symmetry-breaking sector (minimal SM: elementary scalar doublet)

LHC (ATLAS, CMS) are being built to definitively settle this crucial point after the inputs from LEP and Tevatron (with possible future input from ILC/CLIC)

Impossible to condense in three lectures
more than 40 years of theoretical activity
about 20 years of experimental preparation
with thousands of researchers actively
working on different facets of this problem

My goal for these lectures:

A broad-brush updated overview
balancing the different ingredients
contributing (now) to the global picture

Not many experimental details (still time for
an experimentalist's overview in 2008-AT)

Plan

1. “Theory”

The Higgs mechanism in the Standard Model; triviality and stability; hierarchy problem(s); supersymmetry; unitarity and equivalence theorem; alternatives at the LHC.
What is sure vs. likely vs. possible.

2. “Phenomenology”

SM decays and branching ratios; LEP direct bounds; electroweak precision tests; production mechanisms at hadron colliders.
Some plausible BSM variations.

3. “Experiment”

SM Higgs signals at the Tevatron and the LHC; BSM effects/additional signals.
Some scenarios for the LHC

The Higgs mechanism

Goldstone Theorem (1961): spontaneously broken continuous global (=rigid) symmetries imply massless spin-zero bosons

Higgs mechanism (1964) [important previous insights by Schwinger (1957), Anderson (1962), Englert-Brout (1964)]: for local (=gauge) symmetries, would-be-Goldstone boson provides the longitudinal d.o.f. of massive vector boson

Very general phenomenon, with many diverse realizations (e.g. BCS-superconductivity, as discussed by Anderson)

Does not require the existence of an elementary scalar field!

No time here to go deep into QFT aspects: will review first minimal SM realization, then discuss possible alternatives

The Higgs mechanism in the SM

The established building blocks of the Standard Model

Gauge group: $G = SU(3)_C \times SU(2)_L \times U(1)_Y$ $[Q = T_{3L} + Y]$

$$\mathcal{L}_{YM} = -\frac{1}{4} G^{\mu\nu\,A} G^A_{\mu\nu} - \frac{1}{4} W^{\mu\nu\,I} W^I_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu}$$

Fermion content: 3 generations of quarks and leptons

$$q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix} \sim (3, 2, +1/6) \qquad l_L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (1, 2, -1/2)$$

$$u_R \sim (3, 1, +2/3) \qquad d_R \sim (3, 1, -1/3) \qquad e_R \sim (1, 1, -1)$$

$$\mathcal{L}_F = i\overline{\Psi}\gamma^\mu D_\mu \Psi \qquad D_\mu = \partial_\mu - i g_S G^A_\mu \lambda^A - i g W^I_\mu \frac{\tau^I}{2} - i g' B_\mu Y$$

Minimal SM: elementary scalar field

$$\phi \equiv \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \sim (1,2,+1/2)$$

SM Higgs doublet

$$\mathcal{L}_S = (D_\mu\phi)^\dagger (D^\mu\phi) - V \qquad V = \mu^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2$$

(spontaneous breaking of the gauge symmetry)

$$\mathcal{L}_Y = \overline{q_L}\, Y^U u_R \tilde{\phi} + \overline{q_L}\, Y^D d_R \phi + \overline{l_L}\, Y^E e_R \phi + \text{h.c.}$$

$$\tilde{\phi} \equiv (i\sigma^2\phi^*) = \begin{pmatrix} \varphi^{0*} \\ -\varphi^- \end{pmatrix} \sim (1,2,-1/2)$$

conjugate doublet

(explicit breaking of the global flavour symmetry)

Picture confirmed so far with impressive precision

Spontaneous breaking of the gauge symmetry

$$\lambda > 0 \quad \& \quad \mu^2 < 0 \quad \Rightarrow \quad \langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \qquad v = \sqrt{\frac{-\mu^2}{\lambda}}$$

$SU(2)_L \times U(1)_Y$ ➔ $U(1)_Q$ $\qquad \Theta^i$ = broken generators

Spectrum easily discussed in the Unitary Gauge:

$$\phi = e^{\frac{i\alpha^i(x)\Theta^i}{v}} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad \Rightarrow \quad \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

Higgs boson (h) mass and self-interactions:

$$V \Rightarrow -\frac{\lambda}{4} v^4 + \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

$$m_h^2 = 2\lambda v^2 = -2\mu^2$$ undetermined

(v will be fixed in terms of G_F)

Gauge boson masses and gauge-Higgs interactions:

$$D_\mu \phi = \left(\partial_\mu - ig\frac{\tau^I}{2}W_\mu^I - ig'\frac{1}{2}B_\mu\right)\frac{1}{\sqrt{2}}\left(\begin{array}{c} 0 \\ v+h \end{array}\right)$$

$$\downarrow$$

$$|D_\mu\phi|^2 = \frac{1}{2}(\partial^\mu h)(\partial_\mu h) + \left[\frac{g^2v^2}{4}W^{\mu +}W_\mu^- + \frac{(g^2+g'^2)v^2}{8}Z^\mu Z_\mu\right]\left(1+\frac{h}{v}\right)^2$$

$$W_\mu^\pm = \frac{W_\mu^1 \mp iW_\mu^2}{\sqrt{2}} \quad Z_\mu = \sin\theta_W B_\mu - \cos\theta_W A_\mu^3 \quad A_\mu = \cos\theta_W B_\mu + \sin\theta_W A_\mu^3 \quad \tan\theta_W = \frac{g'}{g}$$

$$\downarrow$$

$$m_W^2 = \frac{g^2v^2}{4} \qquad m_Z^2 = \frac{(g^2+g'^2)v^2}{4} \qquad m_\gamma = 0$$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8m_W^2} = \frac{1}{2v^2} \quad \Rightarrow \quad v \simeq 246\ \mathrm{GeV}$$

Fermion masses and interactions:

$$\mathcal{L}_Y \Rightarrow (\overline{u_L}\, Y^U\, u_R + \overline{d_L}\, Y^D\, d_R + \overline{e_L}\, Y^E\, e_R)\frac{(v+h)}{\sqrt{2}} + \text{h.c.}$$

$$= (\overline{u_L}\, M^U\, u_R + \overline{d_L}\, M^D\, d_R + \overline{e_L}\, M^E\, e_R)\left(1 + \frac{g}{2m_W}h\right) + \text{h.c.}$$

Move to fermion mass eigenstates

$$u_L \to V_L^u\, u_L \qquad u_R \to V_R^u\, u_R \qquad d_L \to V_L^d\, d_L \qquad \ldots$$

$$\mathcal{L}_Y \Rightarrow -(m_t\, \overline{t_L}\, t_R + m_b\, \overline{b_L}\, b_R + \ldots)\left(1 + \frac{g}{2m_W}h\right) + \text{h.c.}$$

$$\mathcal{L}_{g.int} = \frac{g}{2\sqrt{2}}(J_W^\mu W_\mu^- + J_W^{\mu\dagger} W_\mu^+) + e\, J_{EM}^\mu A_\mu + \frac{g^2 + g'^2}{2} J_Z^\mu Z_\mu$$

$$J_W^\mu = 2(\overline{e_L}\gamma^\mu \nu_L + \overline{d_L}\gamma^\mu V_{CKM} u_L) \qquad (diagonal\ J_{EM}^\mu,\, J_Z^\mu)$$

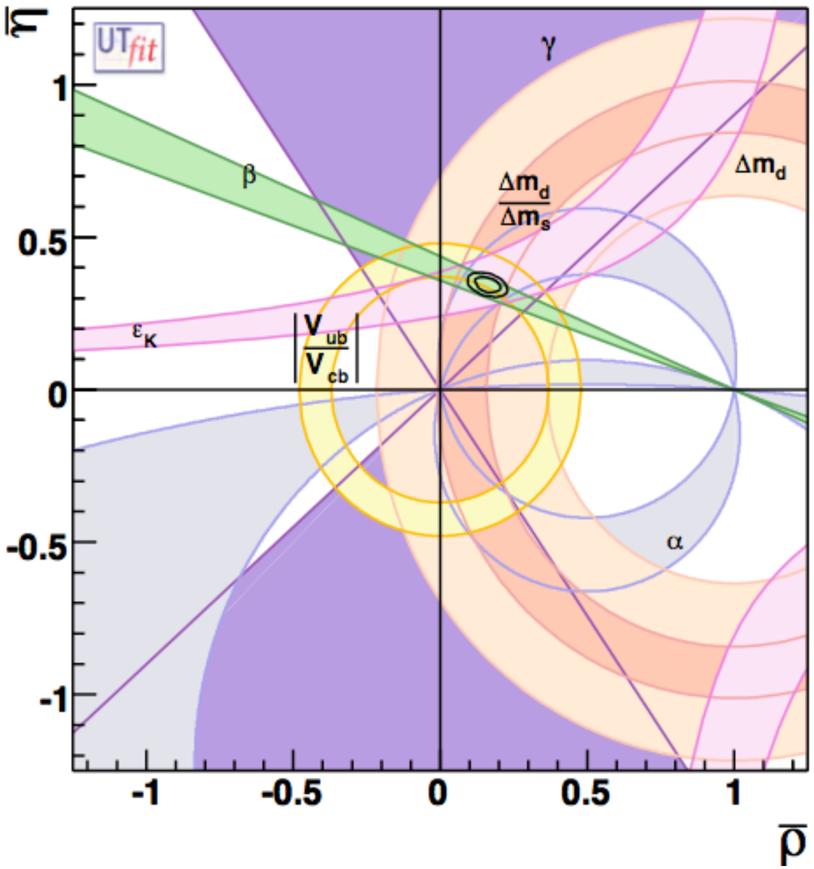
$$V_{CKM} = V_L^{d\dagger} V_L^u$$ only source of flavour/CP violation

(in renormalizable operators made of SM fields)

Precision tests of flavour breaking

Impressive recent progress, and, still:
no significant deviation from SM found

The unitarity triangle



Some recent examples:

Δm_s CDF (& D0)

$K^+ \to \pi^+ \nu\nu$
$\Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$ (NA48)

CP-violation in B system
Rare B decays
UT from tree-level processes
(Belle, BABAR, CDF, D0)

and some older ones:

$B \to X_s \gamma \quad B \to X_s l^+ l^- \quad \mu \to e\gamma$

The custodial symmetry

[Sikivie-Susskind-Voloshin-Zakharov, 1980]

Minimal SM (tree level): $\rho_0 \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$ Veltman's rho parameter

General (I_i, I_{3i}, v_i): $\rho_0 = \frac{\sum_i [I_i(I_i+1) - I_{3i}^2] v_i^2}{2\sum_i I_{3i}^2 v_i^2}$

Can be interpreted in terms of a symmetry (also BSM)

$$\mathcal{L}_m = \frac{1}{2} m_W^2 (W_{1\mu} W_1^\mu + W_{2\mu} W_2^\mu) + \frac{1}{2} (W_{3\mu}\, B_\mu) \begin{pmatrix} M^2 & M'^2 \\ M'^2 & M''^2 \end{pmatrix} \begin{pmatrix} W_3^\mu \\ B^\mu \end{pmatrix}$$

$$m_\gamma = 0 \quad \Rightarrow \quad M^2 M''^2 = M'^4 \quad M^2 + M''^2 = m_Z^2 \quad \Rightarrow \quad \rho = 1 \leftrightarrow M^2 = m_W^2$$

$$V = V(\phi^\dagger \phi) \ \text{ invariant under } \ O(4) \sim SU(2)_L \times SU(2)_R$$

$$\text{symmetry broken by} \langle \phi \rangle \text{ to } SU(2)_V \quad \Rightarrow \quad \rho_0 = 1$$

Largest SM quantum correction controlled by m_t-m_b

➔ could estimate m_t before direct top discovery

Effective potential and running parameters

After including quantum corrections (in a suitable scheme)

$$V_{eff}(\phi) = \mu^2(Q^2)\ \phi^\dagger\phi + \lambda(Q^2)\ (\phi^\dagger\phi)^2 + \log - \text{terms}$$

Leading effects absorbed into running parameters

$$\mu^2(Q^2) \quad \lambda(Q^2) \qquad Q = \text{renormalization scale}$$

as long as the log-terms are small (Q of order v)

$$v^2 \simeq -\frac{\mu^2(v^2)}{\lambda(v^2)} \qquad m_h^2 \simeq 2\,\lambda(v^2)\,v^2 \qquad m_t^2 \simeq \frac{Y_t(v^2)\,v^2}{2}$$

Renormalization group equations:

$$\frac{d\lambda}{d\log Q^2} = \frac{3}{16\pi^2}[4\,\lambda^2 - Y_t^4 + 2\,\lambda\,Y_t^2 + \mathcal{O}(g^2)] \qquad \text{etc.}$$

The SM as an effective theory

Λ = effective UV cutoff (not necessarily universal)
= the scale of some (unspecified) new physics

$$L_{eff}^{SM} = \Lambda^4 + \Lambda^2 \Phi^2 \qquad (\Lambda^{n>0} \Rightarrow \textit{ hierarchy problems!})$$

$$+ (D\Phi)^2 + \overline{\Psi}\, \not{D} \Psi + F \cdot F + F \cdot \widetilde{F} + \overline{\Psi}\Psi\Phi + \Phi^4$$

$$(\textit{controllable } \log\Lambda \textit{ dependence via quantum corrections})$$

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

$$(\Lambda^{n<0} \Rightarrow EW \textit{ tests}, \textit{ flavour tests}, \not{B}, \not{L}, \ldots)$$

Higgs mass vs. the scale of new physics

(Cabibbo, Maiani, Parisi, Petronzio 1979, …)

$$\frac{d\lambda}{d\log Q^2} = \frac{3}{16\pi^2}[4\,\lambda^2 - Y_t^4 + 2\,\lambda\,Y_t^2 + \mathcal{O}(g^2)]$$

The triviality bound (given m_t and Λ):

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

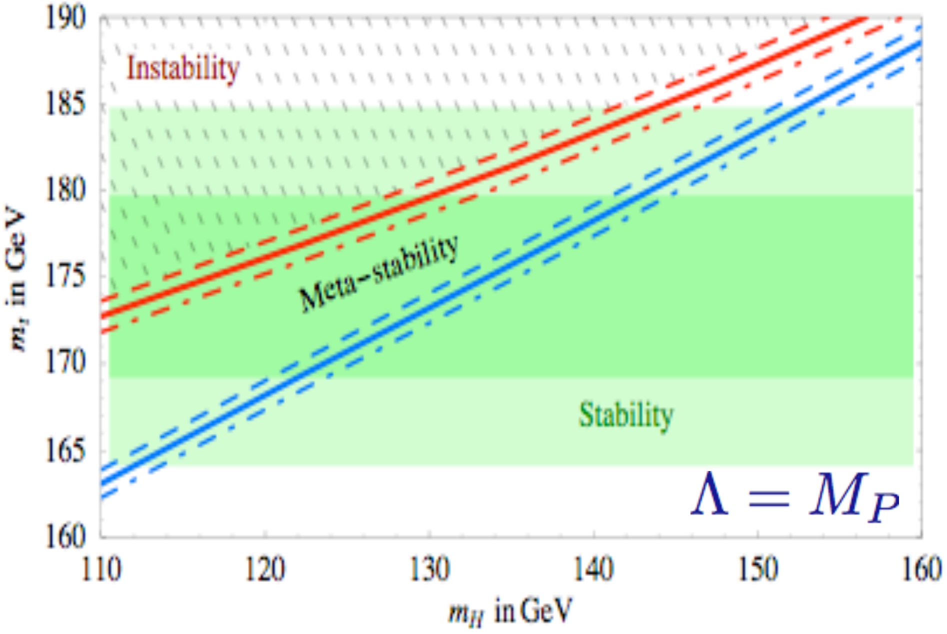
$m_H <$ 200 GeV if $\Lambda \sim M_P \longrightarrow m_H <$ 600 GeV if $\Lambda \sim$ 1 TeV

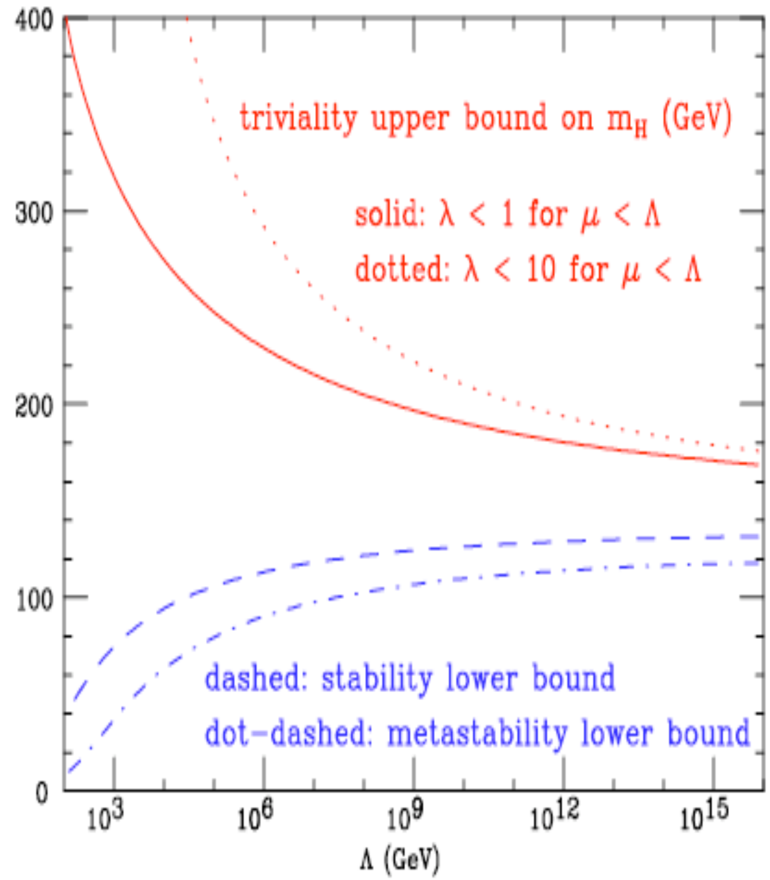
The stability bound (given m_t and Λ):

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 Λ.

Some illustrative pictures

1) Absolute stability
2) High-T fluctuations
3) T=0 quantum fluctuations





[Isidori-Ridolfi-Strumia, hep-ph/0104016]

Naturalness [Wilson; 't Hooft; …]

coefficients small only because of symmetries

electron mass m_e in QED naturally small
chiral symmetry ➔ no linear dependence on cutoff
could have been used in NR theory to predict positron

$$\delta m_e \sim \alpha \Lambda \quad \rightarrow \quad \delta m_e \sim \alpha m_e \log \ldots$$

4-fermion FCNC "box diagram" with 3 light quarks

$$G_F^2 \Lambda^2 \sim G_F^2 m_W^2 \;\; too\ large! \quad \rightarrow \quad G_F^2 m_c^2 \;\; OK$$

Natural solution: GIM mechanism! New physics: charm!

Another example: charged/neutral pion mass difference

Naturalness works!

Naturalness problem of the SM

Higgs mass term (weak scale): gauge hierarchy problem

No quantum SM symmetry recovered for $m_H \rightarrow 0$

(scale invariance broken by quantum corrections and UV physics)

SM unnatural unless New Physics at the LHC scale

$$\delta m_H^2 \sim -\frac{3\,h_t^2}{8\,\pi^2}\Lambda^2 < O(m_H^2) \quad \rightarrow \quad \Lambda < O(600) \times \left(\frac{m_h}{200}\right)\ GeV$$

The lighter the Higgs, the lower the scale of New Physics!

A worse naturalness problem (when gravity is included) is the vacuum energy (10^{-3}eV scale): cosmological constant problem

No natural solution found so far, but not excluded either: modifications of gravity at sub-mm scales still possible even if bounds considerably improved in the last years

Today's puzzle

[stressed, e.g., by Barbieri and Strumia: little hierarchy problem]

SM with light Higgs is in precise agreement with data

Naturalness pushes for a low scale of new physics:

$$\Lambda_{NP} < O(500)\ GeV$$

Precision tests push for a high scale of new physics:

$$\mathcal{L}_{eff}^{NP} = \frac{1}{\Lambda_{NP}^2}[c_1(\bar{e}\gamma^\mu e)^2 + c_2 W_{\mu\nu}^I B^{\mu\nu} H^\dagger \sigma^I H + \ldots]$$

$$c_i = O(1) \quad \Rightarrow \quad \Lambda_{NP} > \text{several } TeV$$

Conflict avoided with weakly coupled new physics
affecting low-energy observables only via loops
(and decoupled from flavour-violating operators)

$$c_i \sim \frac{\alpha}{2\pi} \quad and \quad \Lambda_{NP} \sim O(500)\ GeV$$

End of Lecture 1