Higgs Physics

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I: EWSB in the SM

- **The Standard Model in brief**
- **The Higgs mechanism**
- **Constraints on M_H**

II: Higgs decays

III: Higgs production a hadron colliders

IV: Higgs discovery and after

?? EWSB in SUSY theories ??

1. The Standard Model in brief

The SM of the electromagnetic, weak and strong interactions is:

- **a relativistic quantum field theory,**
- **based on local gauge symmetry: invariance under symmetry group,**
- **more or less a carbon–copy of QED, the theory of electromagnetism.**

QED: invariance under local transformations of the abelian group U(1)$_{\rm Q}$

– transformation of electron field: $\Psi(x) \to \Psi'(x) = e^{ie\alpha(x)}\Psi(x)$

– transformation of photon field: $A_\mu(x) \to A'_\mu(x) = A_\mu(x) - \frac{1}{e}\partial_\mu \alpha(x)$

The Lagrangian density is invariant under above field transformations

$$\mathcal{L}_{\rm QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\, D_\mu \gamma^\mu \Psi \ \ - m_e \bar{\Psi}\Psi$$

field strength $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ **and cov. derivative** $D_\mu = \partial_\mu - ieA_\mu$

Very simple and extremely successful theory!

– minimal coupling: the interactions/couplings uniquely determined,

– renormalisable, perturbative, unitary (predictive), very well tested...

1. The Standard Model: brief introduction

The SM is based on the local gauge symmetry group

$$\mathrm{G_{SM} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y}$$

- **The group $\mathrm{SU(3)_C}$ describes the strong force:**

– interaction between quarks which are SU(3) triplets: q, q , q

– mediated by 8 gluons, $\mathbf{G^a_\mu}$ corresponding to 8 generators of $\mathbf{SU(3)_C}$

Gell-Man 3×3 matrices: $\mathbf{[T^a, T^b] = i f^{abc} T_c}$ with $\mathbf{Tr[T^a T^b] = \frac{1}{2}\delta_{ab}}$

– asymptotic freedom: interaction "weak" at high energy, $\alpha_\mathbf{s} = \frac{\mathbf{g_s^2}}{4\pi} \ll 1$

The Lagrangian of the theory is given by:

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4}\mathbf{G^a_{\mu\nu} G_a^{\mu\nu} + i \sum_i \bar{q}_i (\partial_\mu - i g_s T_a G^a_\mu)\gamma^\mu q_i} \ \ (-\sum_\mathbf{i} \mathbf{m_i \bar{q}_i q_i})$$

with $\mathbf{G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s\, f^{abc} G^b_\mu G^c_\nu}$

The interactions/couplings are then uniquely determined:

– fermion gauge boson couplings : $-\mathbf{g_i}\overline{\psi}\mathbf{V}_\mu \gamma^\mu \psi$

– V self-couplings : $\mathbf{i g_i}\, \mathrm{Tr}(\partial_\nu \mathbf{V}_\mu - \partial_\mu \mathbf{V}_\nu)[\mathbf{V}_\mu, \mathbf{V}_\nu] + \frac{1}{2}\mathbf{g_i^2}\, \mathrm{Tr}[\mathbf{V}_\mu, \mathbf{V}_\nu]^2$

1. The Standard Model: brief introduction

• $\mathrm{SU(2)_L \times U(1)_Y}$ **describes the electroweak interaction:**

– **between the three families of quarks and leptons:** $\mathbf{f_{L/R} = \frac{1}{2}(1 \mp \gamma_5)f}$

$$\mathbf{I_f^{3L,3R} = \pm\frac{1}{2}, 0 \;\Rightarrow\; L = \binom{\nu_e}{e^-}_L,\; R = e_R^-,\; Q = \binom{u}{d}_L,\; u_R,\; d_R}$$

$$\mathbf{Y_f = 2Q_f - 2I_f^3 \Rightarrow Y_L = -1, Y_R = -2, Y_Q = \frac{1}{3}, Y_{u_R} = \frac{4}{3}, Y_{d_R} = -\frac{2}{3}}$$

Same holds for the two other generations: $\mu, \nu_\mu, \mathbf{c}, \mathbf{s};\; \tau, \nu_\tau, \mathbf{t}, \mathbf{b}$.

There is no $\nu_{\mathbf{R}}$ **(and neutrinos are and stay exactly massless)**

– **mediated by the** $\mathbf{W_\mu^i}$ **(isospin) and** $\mathbf{B_\mu}$ **(hypercharge) gauge bosons**

the gauge bosons, corresp. to generators, are exactly massless

$$\mathbf{T^a = \frac{1}{2}\tau^a\,; \quad [T^a, T^b] = i\epsilon^{abc}T_c \;\; \text{and} \;\; [Y, Y] = 0}$$

Lagrangian simple: with fields strengths and covariant derivatives

$$\mathbf{W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g_2 \epsilon^{abc} W^b_\mu W^c_\nu,\; B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu}$$

$$\mathbf{D_\mu \psi = \left(\partial_\mu - igT_aW^a_\mu - ig'\frac{Y}{2}B_\mu\right)\psi\,,\;\; T^a = \frac{1}{2}\tau^a}$$

$$\mathcal{L}_{\mathrm{SM}} = \mathbf{-\frac{1}{4}W^a_{\mu\nu}W^{\mu\nu}_a - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \bar{F}_{Li}\, iD_\mu\gamma^\mu\, F_{Li} + \bar{f}_{Ri}\, iD_\mu\gamma^\mu\, f_{R_i}}$$

1. The Standard Model: brief introduction

But if gauge boson and fermion masses are put by hand in $\mathcal{L}_{\rm SM}$

$\frac{1}{2}{\rm M}_{\rm V}^2 {\rm V}^\mu {\rm V}_\mu$ **and/or** ${\rm m_f \bar{f} f}$ **terms: breaking of gauge symmetry.**

This statement can be visualized by taking the example of QED where the photon is massless because of the local ${\rm U(1)_Q}$ local symmetry:

$$\mathbf{\Psi(x) \to \Psi'(x) = e^{ie\alpha(x)}\Psi(x)\ ,\ A_\mu(x) \to A'_\mu(x) = A_\mu(x) - \frac{1}{e}\partial_\mu \alpha(x)}$$

• For the photon (or B field for instance) mass we would have:

$$\mathbf{\frac{1}{2}M_A^2 A_\mu A^\mu \to \frac{1}{2}M_A^2 (A_\mu - \frac{1}{e}\partial_\mu \alpha)(A^\mu - \frac{1}{e}\partial^\mu \alpha) \neq \frac{1}{2}M_A^2 A_\mu A^\mu}$$

and thus, gauge invariance is violated with a photon mass.

• For the fermion masses, we would have (e.g. for the electron):

$$\mathbf{m_e \bar{e} e = m_e \bar{e}\left(\frac{1}{2}(1-\gamma_5) + \frac{1}{2}(1+\gamma_5)\right)e = m_e(\bar{e}_R e_L + \bar{e}_L e_R)}$$

manifestly non–invariant under SU(2) isospin symmetry transformations.

We need a less “brutal” way to generate particle masses in the SM:

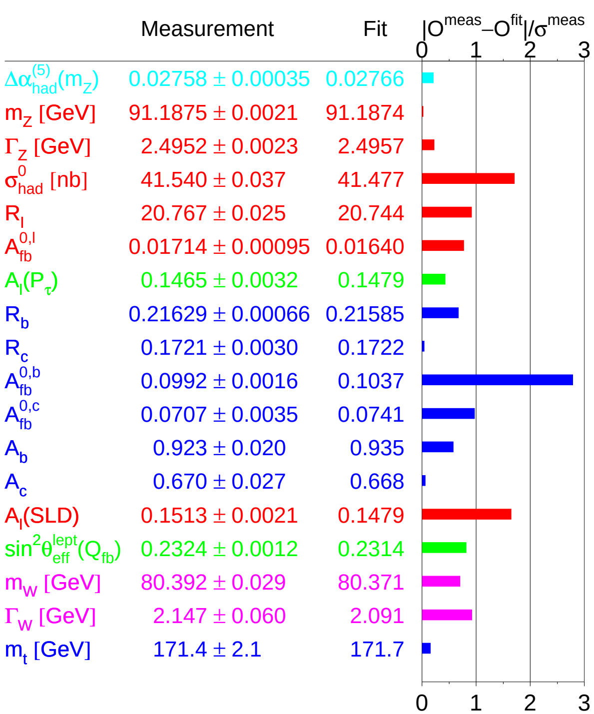
$\Rightarrow$ The Brout-Englert-Higgs mechanism $\Rightarrow$ the Higgs particle H.

1. The Standard Model: brief introduction

⇒ **High precision tests of the SM performed at quantum level: 1%–0.1%**

The SM describes precisely (almost) all available experimental data!

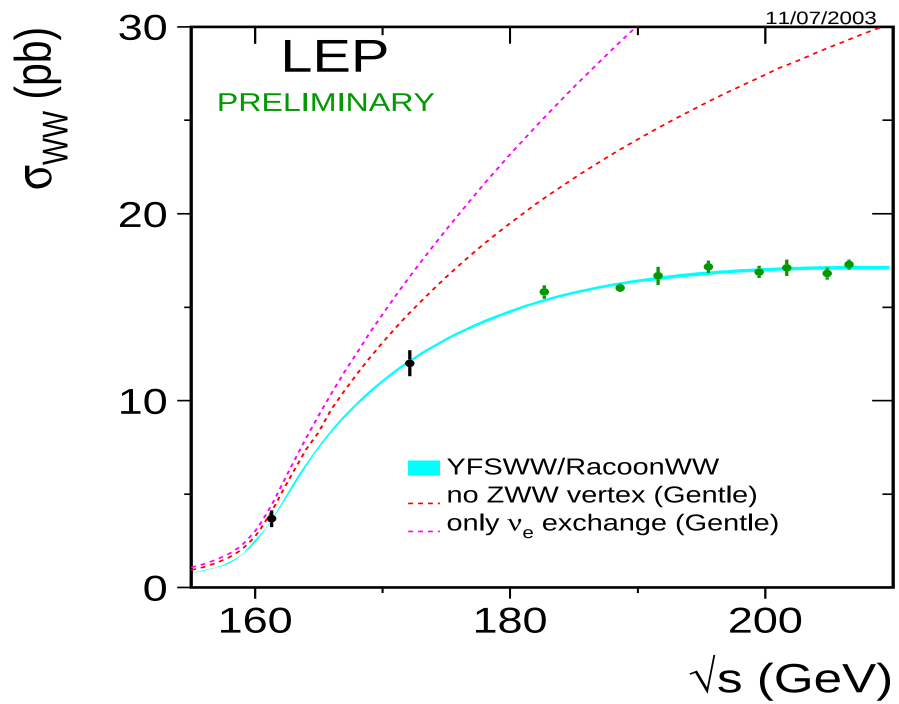
- **Couplings of fermions to γ,Z**
- **Z,W boson properties**
- **measure/running of α_S**



LEP1, SLC, LEP2, Tevatron

- **SM gauge structure**
- **Properties of W bosons**

LEP2, Tevatron



- **Physics of top&bottom quarks, QCD**

Tevatron, HERA and B factories

2. EWSB in the SM

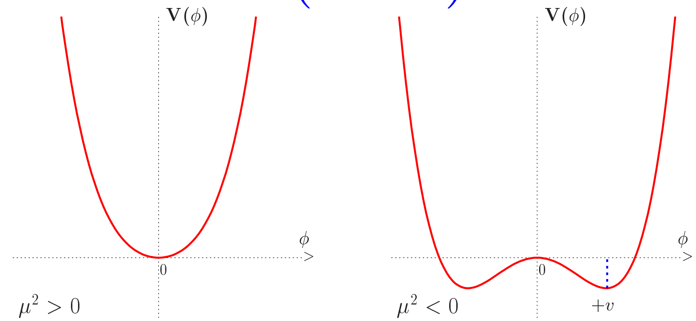
In the SM, if gauge boson and fermion masses are put by hand in $\mathcal{L}_{\rm SM}$

breaking of gauge symmetry $\Rightarrow$ spontaneous EW symmetry breaking

$\Rightarrow$ introduce a doublet of complex scalar fields: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$, $Y_\Phi = +1$

with a Lagrangian that is invariant under $\mathrm{SU(2)_L \times U(1)_Y}$

$$\mathcal{L}_S = (D^\mu \Phi)^\dagger (D_\mu \Phi) - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$



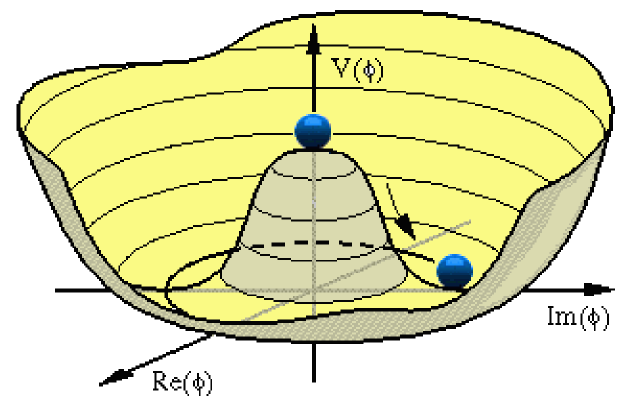
$\mu^2 > 0$: 4 scalar particles.

$\mu^2 < 0$: Φ develops a vev:

$$\langle 0 | \Phi | 0 \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

$$\text{with vev} \equiv v = (-\mu^2/\lambda)^{\frac{1}{2}}$$

– symmetric minimum: instable
– true vaccum: degenerate



$\Rightarrow$ to obtain the physical states,

write $\mathcal{L}_S$ with the true vacuum:

2. EWSB in SM: mass generation

- **Write Φ in terms of four fields $\theta_{1,2,3}(x)$ and H(x) at 1st order:**

$$\Phi(x) = e^{i\theta_a(x)\tau^a(x)/v} \frac{1}{\sqrt{2}}\binom{0}{v+H(x)} \simeq \frac{1}{\sqrt{2}}\binom{\theta_2+i\theta_1}{v+H-i\theta_3}$$

- **Make a gauge transformation on Φ to go to the unitary gauge:**

$$\Phi(x) \to e^{-i\theta_a(x)\tau^a(x)}\, \Phi(x) = \frac{1}{\sqrt{2}}\binom{0}{v+H(x)}$$

- **Then fully develop the term $|D_\mu\Phi)|^2$ of the Lagrangian $\mathcal{L}_S$:**

$$|D_\mu\Phi)|^2 = \left|\left(\partial_\mu - ig_1\frac{\tau_a}{2}W_\mu^a - i\frac{g_2}{2}B_\mu\right)\Phi\right|^2$$

$$= \frac{1}{2}\left|\begin{pmatrix} \partial_\mu - \frac{i}{2}(g_2 W_\mu^3 + g_1 B_\mu) & -\frac{ig_2}{2}(W_\mu^1 - iW_\mu^2) \\ -\frac{ig_2}{2}(W_\mu^1 + iW_\mu^2) & \partial_\mu + \frac{i}{2}(g_2 W_\mu^3 - g_1 B_\mu) \end{pmatrix} \binom{0}{v+H}\right|^2$$

$$= \frac{1}{2}(\partial_\mu H)^2 + \frac{1}{8}g_2^2(v+H)^2|W_\mu^1 + iW_\mu^2|^2 + \frac{1}{8}(v+H)^2|g_2 W_\mu^3 - g_1 B_\mu|^2$$

- **Define the new fields $W_\mu^\pm$ and Z_μ [A_μ is the orthogonal of Z_μ]:**

$$W^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp W_\mu^2)\ ,\ Z_\mu = \frac{g_2 W_\mu^3 - g_1 B_\mu}{\sqrt{g_2^2+g_1^2}}\ ,\ A_\mu = \frac{g_2 W_\mu^3 + g_1 B_\mu}{\sqrt{g_2^2+g_1^2}}$$

$$\text{with}\ \ \sin^2\theta_W \equiv g_2/\sqrt{g_2^2+g_1^2} = e/g_2$$

2. EWSB in SM: mass generation

- **And pick up the terms which are bilinear in the fields $W^{\pm}, Z, A$:**

$$M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu + \frac{1}{2} M_A^2 A_\mu A^\mu$$

$\Rightarrow$ **3 degrees of freedom for $W_L^{\pm}, Z_L$ and thus $M_{W^\pm}, M_Z$:**

$$M_W = \frac{1}{2} v g_2 \, , \; M_Z = \frac{1}{2} v \sqrt{g_2^2 + g_1^2} \, , \; M_A = 0 \, ,$$

with the value of the vev given by: $v = 1/(\sqrt{2} G_F)^{1/2} \sim 246 \, \mathrm{GeV}$.

$\Rightarrow$ **The photon stays massless, $U(1)_{QED}$ is preserved.**

- **For fermion masses, use same doublet field Φ and its conjugate field $\tilde{\Phi} = i\tau_2 \Phi^*$ and introduce $\mathcal{L}_{Yuk}$ which is invariant under SU(2)xU(1):**

$$\mathcal{L}_{Yuk} = -f_e (\bar{e}, \bar{\nu})_L \Phi e_R - f_d (\bar{u}, \bar{d})_L \Phi d_R - f_u (\bar{u}, \bar{d})_L \tilde{\Phi} u_R + \cdots$$

$$= -\frac{1}{\sqrt{2}} f_e (\bar{\nu}_e, \bar{e}_L) \binom{0}{v+H} e_R \cdots = -\frac{1}{\sqrt{2}} (v + H) \bar{e}_L e_R \cdots$$

$$\Rightarrow m_e = \frac{f_e \, v}{\sqrt{2}} \; , \; m_u = \frac{f_u \, v}{\sqrt{2}} \; , \; m_d = \frac{f_d \, v}{\sqrt{2}}$$

With same Φ, we have generated gauge boson and fermion masses, while preserving SU(2)xU(1) gauge symmetry (which is now hidden)!

What about the residual degree of freedom?

2. EWSB in SM: the Higgs boson

It will correspond to the physical spin–zero scalar Higgs particle, H.

The kinetic part of H field, $\frac{1}{2}(\partial_\mu H)^2$**, comes from** $|D_\mu \Phi)|^2$ **term.**

Mass and self-interaction part from $V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$**:**

$$V = \frac{\mu^2}{2}(0, v + H)\binom{0}{v+H} + \frac{\lambda}{2}|(0, v + H)\binom{0}{v+H}|^2$$

Doing the exercise you find that the Lagrangian containing H is,

$$\mathcal{L}_H = \frac{1}{2}(\partial_\mu H)(\partial^\mu H) - V = \frac{1}{2}(\partial^\mu H)^2 - \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$

The Higgs boson mass is given by: $M_H^2 = 2\lambda v^2 = -2\mu^2$.

The Higgs triple and quartic self–interaction vertices are:

$$g_{H^3} = 3i\, M_H^2/v \,,\; g_{H^4} = 3iM_H^2/v^2$$

What about the Higgs boson couplings to gauge bosons and fermions?

They were almost derived previously, when we calculated the masses:

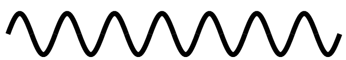
$$\mathcal{L}_{M_V} \sim M_V^2(1 + H/v)^2 \;,\; \mathcal{L}_{m_f} \sim -m_f(1 + H/v)$$

$$\Rightarrow g_{Hff} = im_f/v \,,\; g_{HVV} = -2iM_V^2/v \,,\; g_{HHVV} = -2iM_V^2/v^2$$

Since v is known, the only free parameter in the SM is M_H **or** λ**.**

2. EWSB in SM: W/Z/H at high energies

Propagators of gauge and Goldstone bosons in a general ζ gauge:



$\longrightarrow q$ $\quad \frac{-i}{q^2-M_V^2+i\epsilon}\left[g_{\mu\nu}+(\zeta-1)\frac{q_\mu q_\nu}{q^2-\zeta M_V^2}\right]$

$\zeta=\infty$: **Landau gauge**

$\zeta=1$: **'t Hooft-Feynman**

$\omega^\pm, \omega^0$:

$\longrightarrow q$ $\quad \frac{-i}{q^2-\zeta M_V^2+i\epsilon}$

- **In unitary gauge, Goldstones do not propagate and gauge bosons have usual propagators of massive spin–1 particles (old IVB theory).**
- **At very high energies, $\mathbf{s \gg M_V^2}$, an approximation is $\mathbf{M_V \sim 0}$. The $\mathbf{V_L}$ components of V can be replaced by the Goldstones, $\mathbf{V_L \to w}$.**
- **In fact, the electroweak equivalence theorem tells that at high energies, massive vector bosons are equivalent to Goldstones. In VV scattering e.g.**

$$\mathbf{A(V_L^1 \cdots V_L^n \to V_L^1 \cdots V_L^{n'}) = (i)^n(-i)^{n'} A(w^1 \cdots w^n \to w^1 \cdots w^{n'}}$$

Thus, we simply replace V by w in the scalar potential and use w:

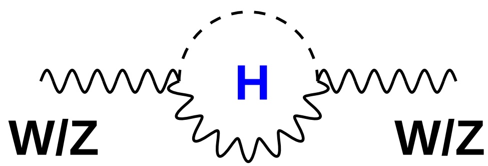
$$\mathbf{V = \frac{M_H^2}{2v}(H^2+w_0^2+2w^+w^-)H + \frac{M_H^2}{8v^2}(H^2+w_0^2+2w^+w^-)^2}$$

3. Constraints on M_H

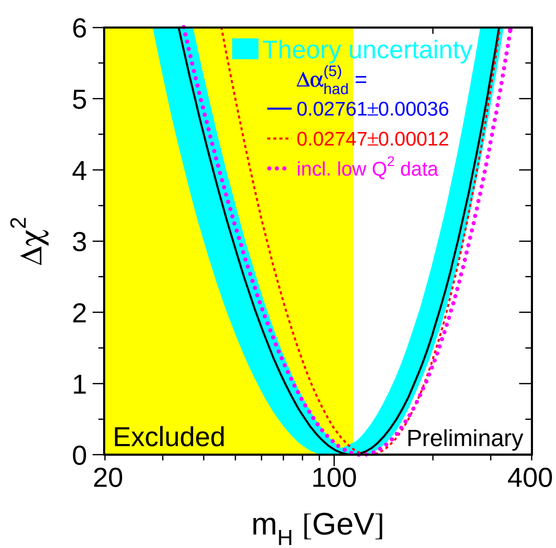
First, there were constraints from pre–LHC experiments....

Indirect Higgs searches:

H contributes to RC to W/Z masses:



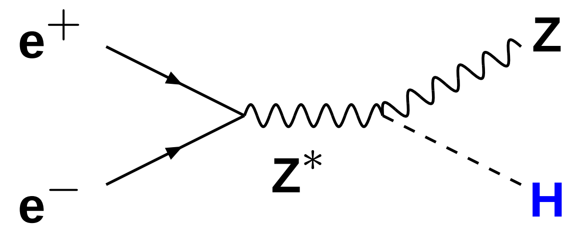
Fit the EW precision measurements:
we obtain $M_H = 92^{+34}_{-26}$ GeV, or



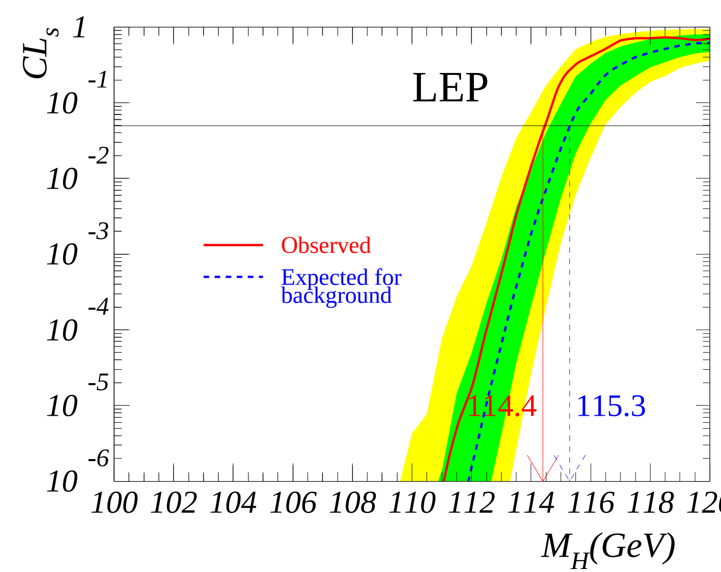
$M_H \lesssim 160$ GeV at 95% CL

Direct searches at colliders:

H looked for in $e^+e^- \to ZH$



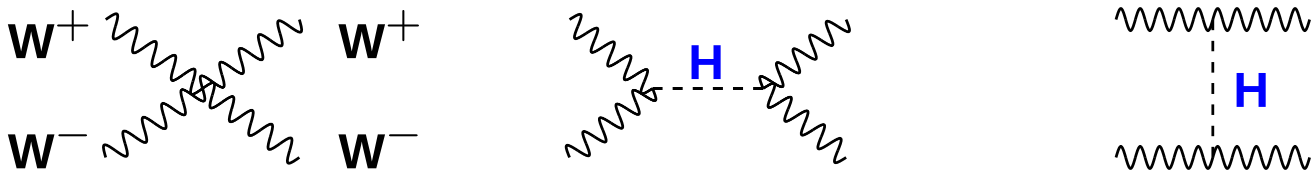
$M_H > 114.4$ GeV @95%CL



Tevatron $M_H \neq 160-175$ GeV

3. Constraints on M_H: perturbative unitarity

Scattering of massive gauge bosons $V_L V_L \to V_L V_L$ at high-energy



Because w interactions increase with energy (q^μ terms in V propagator),

$s \gg M_W^2 \Rightarrow \sigma(w^+w^- \to w^+w^-) \propto s$: $\Rightarrow$ unitarity violation possible!

Decomposition into partial waves and choose J=0 for $s \gg M_W^2$:

$$a_0 = -\frac{M_H^2}{8\pi v^2}\left[1 + \frac{M_H^2}{s-M_H^2} + \frac{M_H^2}{s}\log\left(1 + \frac{s}{M_H^2}\right)\right]$$

For unitarity to be fullfiled, we need the condition $|\mathrm{Re}(a_0)| < 1/2$.

- At high energies, $s \gg M_H^2, M_W^2$, we have: $a_0 \xrightarrow{s \gg M_H^2} -\frac{M_H^2}{8\pi v^2}$

$$\text{unitarity} \Rightarrow M_H \lesssim 870\ \mathrm{GeV} \ \ (M_H \lesssim 710\ \mathrm{GeV})$$

- For a very heavy or no Higgs boson, we have: $a_0 \xrightarrow{s \ll M_H^2} -\frac{s}{32\pi v^2}$

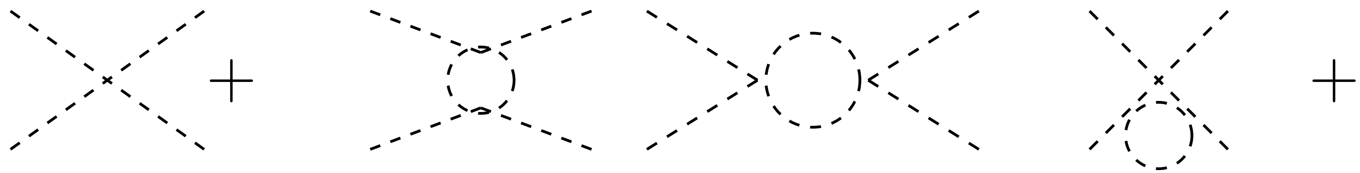
$$\text{unitarity} \Rightarrow \sqrt{s} \lesssim 1.7\ \mathrm{TeV} \ \ (\sqrt{s} \lesssim 1.2\ \mathrm{TeV})$$

Otherwise (strong?) New Physics should appear to restore unitarity.

3. Constraints on M_H: triviality

The quartic coupling of the Higgs boson λ ($\propto M_H^2$) increases with energy.

If the Higgs is heavy: the H contributions to λ is by far dominant



The RGE evolution of λ with Q^2 and its solution are given by:

$$\frac{d\lambda(Q^2)}{dQ^2} = \frac{3}{4\pi^2}\lambda^2(Q^2) \Rightarrow \lambda(Q^2) = \lambda(v^2)\left[1 - \frac{3}{4\pi^2}\lambda(v^2)\log\frac{Q^2}{v^2}\right]^{-1}$$

- If $Q^2 \ll v^2$, $\lambda(Q^2) \to 0_+$: **the theory is trivial (no interaction).**
- If $Q^2 \gg v^2$, $\lambda(Q^2) \to \infty$: **Landau pole at** $Q = v\exp\left(\frac{4\pi^2 v^2}{M_H^2}\right)$.

The SM is valid only at scales before λ becomes infinite:

If $\Lambda_C = M_H,\ \lambda \lesssim 4\pi \Rightarrow M_H \lesssim 650$ GeV

(comparable to results obtained with simulations on the lattice!)

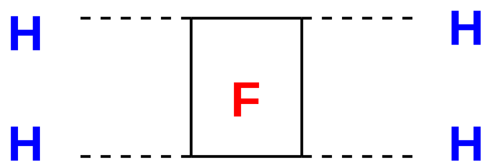
If $\Lambda_C = M_P,\ \lambda \lesssim 4\pi \Rightarrow M_H \lesssim 180$ GeV

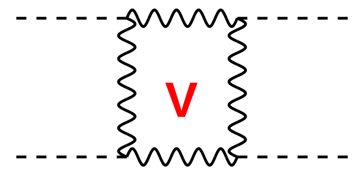
(comparable to exp. limit if SM extrapolated to GUT/Planck scales)

3. Constraints on M_H: vacuum stability

The top quark and gauge bosons also contribute to the evolution of λ.

(contributions dominant (over that of H itself) at low M_H values)





The RGE evolution of the coupling at one–loop is given by

$$\lambda(Q^2) = \lambda(v^2) + \frac{1}{16\pi^2}\left[-12\frac{m_t^4}{v^4} + \frac{3}{16}\left(2g_2^4 + (g_2^2+g_1^2)^2\right)\right]\log\frac{Q^2}{v^2}$$

If λ is small (H is light), top loops might lead to $\lambda(0) < \lambda(v)$:

v is not the minimum of the potentiel and EW vacuum is instable.

$\Rightarrow$ Impose that the coupling λ stays always positive:

$$\lambda(Q^2) > 0 \Rightarrow M_H^2 > \frac{v^2}{8\pi^2}\left[-12\frac{m_t^4}{v^4} + \frac{3}{16}\left(2g_2^4 + (g_2^2+g_1^2)^2\right)\right]\log\frac{Q^2}{v^2}$$

Very strong constraint: $Q = \Lambda_C \sim 1\ \mathrm{TeV} \ \Rightarrow M_H \gtrsim 70$ GeV

(we understand why we have not observed the Higgs bofeore LEP2...)

If SM up to high scales: $Q = M_P \sim 10^{18}\ \mathrm{GeV} \ \Rightarrow M_H \gtrsim 130$ GeV

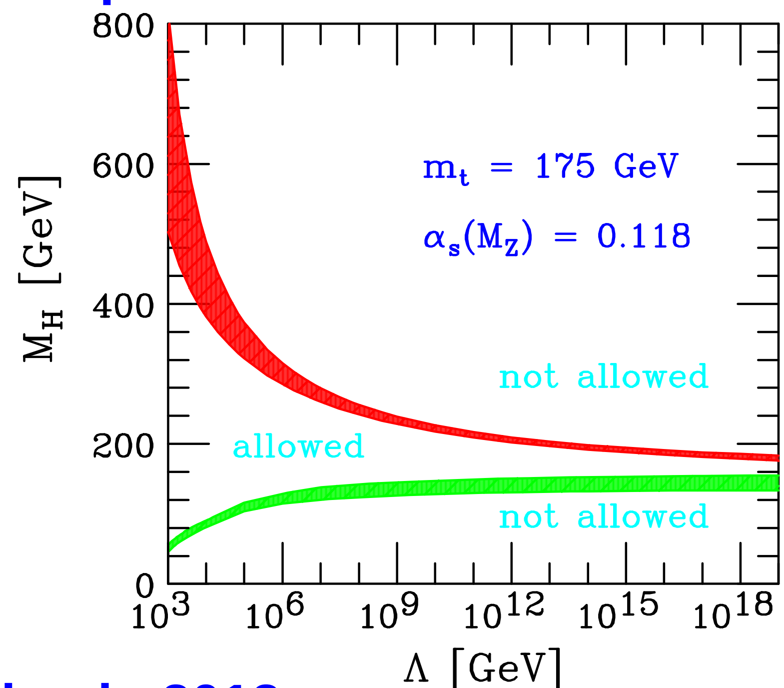
3. Constraints on M_H: triviality+stability

Combine the two constraints and include all possible effects:

– corrections at two loops

– theoretical+exp. errors

– other refinements $\cdots$



$\Lambda_C \approx 1$ TeV $\Rightarrow 70 \lesssim M_H \lesssim 700$ GeV

$\Lambda_C \approx M_{Pl} \Rightarrow 130 \lesssim M_H \lesssim 180$ GeV

Cabibbo, Maiani, Parisi, Petronzio

Hambye, Riesselmann

A more up-to date (full two loop) calculation in 2012:

Degrassi et al., Berzukov et al.

At 2–loop for m_t^{pole}=173.1 GeV:

fully stable vaccum $M_H \gtrsim 129$ GeV...

but vacuum metastable below!

metastability OK: unstable vacuum

but very long lived $\tau_{tunel} \gtrsim \tau_{univ} \cdots$