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Higgs bosons searches at LHC
Part I

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These are preliminary lecture notes, intended only for distribution to participants.

The Higgs at the LHC

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- **The Higgs boson in the Standard Model**
  1. **The Higgs mechanism in the SM**
  2. **Constraints on the Higgs mass**
  3. **SM Higgs decays**
- **The SM Higgs at the LHC**
- **The Higgs boson in SUSY theories**
- **The SUSY Higgs bosons at the LHC**

1. The Higgs mechanism in the SM

[only a slide: more details in the lectures of U. Baur and M. Mangano]

The SM is based on a local gauge symmetry: invariance under

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

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

– interaction between q, q , q mediated by 8 gluons,

– asymptotic freedom: the interaction is “weak” at high energy.

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

– between the three familles of quarks and leptons

$$\mathbf{L} = \binom{\nu_\mathrm{e}}{\mathrm{e}^-}_\mathbf{L},\ \mathbf{e_R^-}\ ;\ \mathbf{Q} = \binom{\mathbf{u}}{\mathbf{d}}_\mathbf{L},\ \mathbf{u_R},\ \mathbf{d_R}\ \times \mathbf{3}\ \mathrm{generations}$$

– mediated by the $\tilde{\mathrm{W}}_\mu$ (isospin) and B_μ (hypercharge) gauge bosons.

- **Lagrangian simple: with fields strenghs and covariant derivatives**

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

$$\mathbf{D}_\mu\psi = \left(\partial_\mu - \mathbf{igT_a W^a_\mu} - \mathbf{ig'}\frac{\mathbf{Y}}{\mathbf{2}}\mathbf{B}_\mu\right)\psi\ ,\quad \mathbf{T^a} = \frac{\mathbf{1}}{\mathbf{2}}\tau^\mathbf{a}$$

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

1. The Higgs in the SM: the potential

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

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

We need a less "brutal" way to generate particle masses in the SM.

In the SM, for the mechanism of spontaneous EW symmetry breaking,

$\Rightarrow$ **introduce a doublet of complex scalar fields**

$$\mathbf{\Phi} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \ \text{ with } \ \mathbf{Y_\Phi = +1}$$

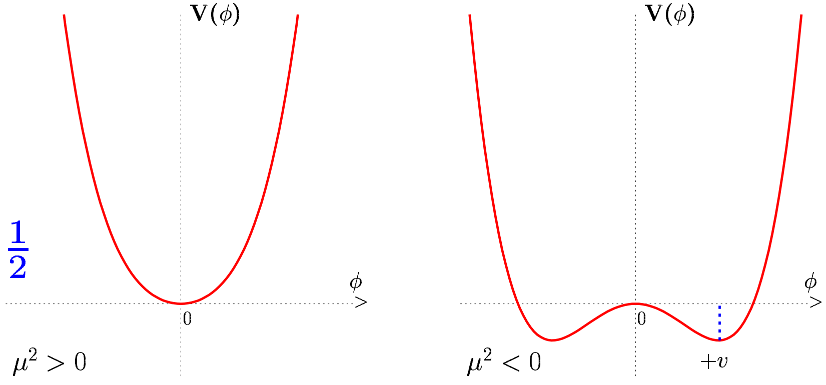
with a Lagrangian that is invariant under $\mathbf{SU(2)_L \times U(1)_Y}$

$$\mathcal{L}_{\mathbf{S}} = (\mathbf{D}^\mu \mathbf{\Phi})^\dagger (\mathbf{D}_\mu \mathbf{\Phi}) - \mu^2 \mathbf{\Phi}^\dagger \mathbf{\Phi} - \lambda (\mathbf{\Phi}^\dagger \mathbf{\Phi})^2$$

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

$\mu^2 < 0$: Φ **develops a vev:**

$$\langle 0 | \Phi | 0 \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}, \ v = \left(-\frac{\mu^2}{\lambda}\right)^{\frac{1}{2}}$$



1. The Higgs in the SM: the physical fields

To obtain the physical states, write $\mathcal{L}_S$ with the true vacuum:

- **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 $\mathcal{L}_S$:**

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

$$= \frac{1}{2}\left|\begin{pmatrix} \partial_\mu - \frac{i}{2}(g_2W_\mu^3 + g_1B_\mu) & -\frac{ig_2}{2}(W_\mu^1 - iW_\mu^2) \\ -\frac{ig_2}{2}(W_\mu^1 + iW_\mu^2) & \partial_\mu + \frac{i}{2}(g_2W_\mu^3 - g_1B_\mu) \end{pmatrix} \binom{0}{v+H}\right|^2$$

$$= \frac{1}{2}(\partial_\mu H)^2 + \frac{1}{8}g_2^2(v+H)^2|W_\mu^1 + iW_\mu^2|^2 + \frac{1}{8}(v+H)^2|g_2W_\mu^3 - g_1B_\mu|^2$$

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

$$W^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp W_\mu^2)\ ,\ Z_\mu = \frac{g_2W_\mu^3 - g_1B_\mu}{\sqrt{g_2^2+g_1^2}}\ ,\ A_\mu = \frac{g_2W_\mu^3 + g_1B_\mu}{\sqrt{g_2^2+g_1^2}}$$

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

1. The Higgs in the SM: the masses

- 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, $U(1)_{\rm QED}$ is preserved.

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

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

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

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

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?

1. The Higgs in the 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.

1. The Higgs in the SM: the Goldstone bosons

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

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

$\zeta = \infty$: 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, $\mathrm{s} \gg \mathrm{M_V^2}$, an approximation is $\mathrm{M_V} \sim 0$. The $\mathrm{V_L}$ components of V can be replaced by the Goldstones, $\mathrm{V_L} \to \omega$.
- In fact, the electroweak equivalence theorem tells that at high energies, massive vector bosons are equivalent to Goldstones. In VV scattering e.g

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

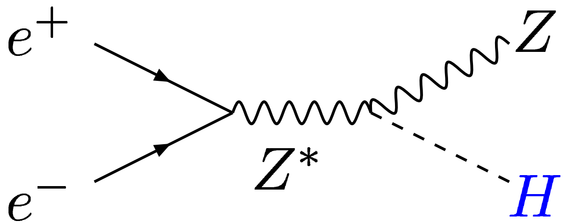
Thus, we simply replace V by w in the scalar potential and use w:

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

2. Constraints on M_H

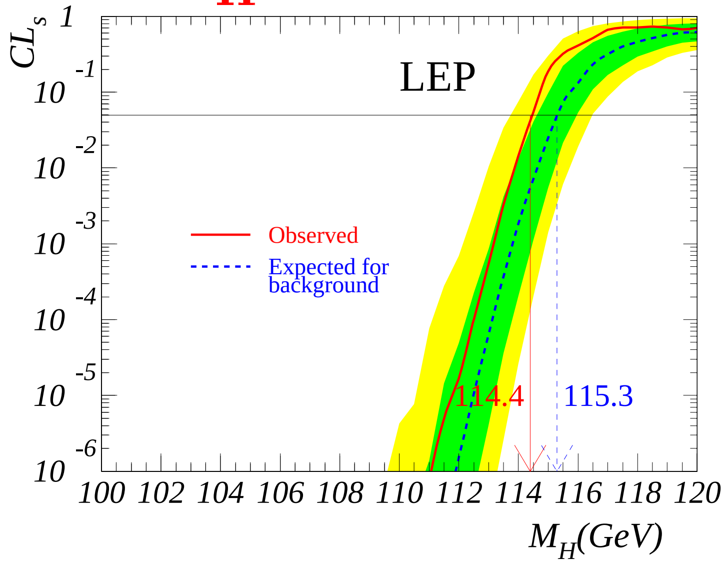
Direct searches at LEP:

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



We have a limit at 95% CL:

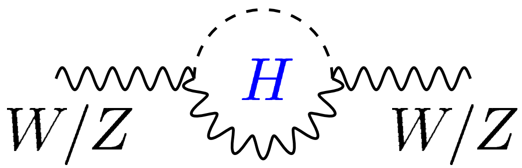
$\mathbf{M_H > 114.4}$ **GeV**



(1.7σ excess at $M_H \sim 116$ GeV)

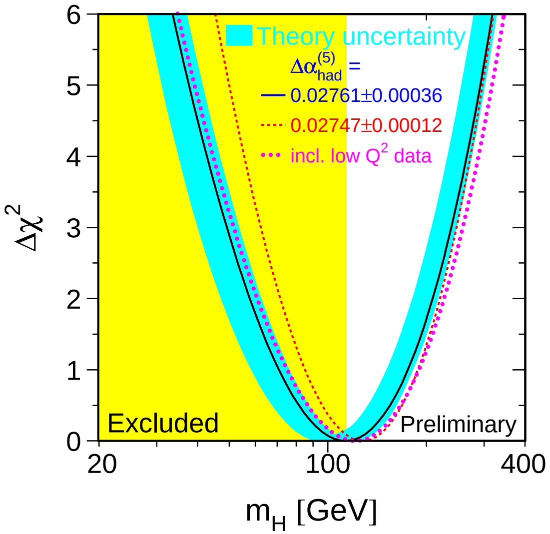
Indirect searches:

H contributes to RC to W/Z masses:



Fit the EW precision measurements:

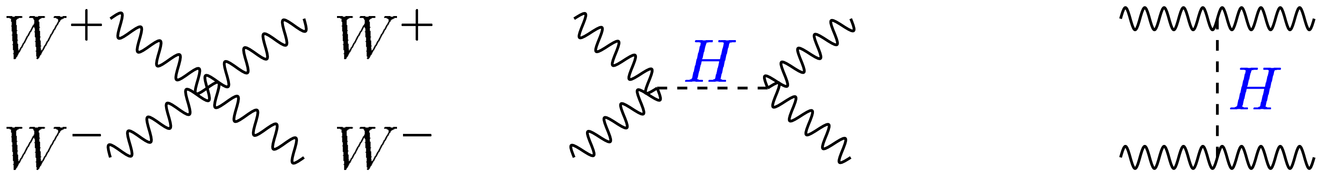
we obtain $\mathbf{M_H = 85^{+39}_{-28}}$ GeV, or



$\mathbf{M_H \lesssim 200}$ **GeV at 95% CL**

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

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

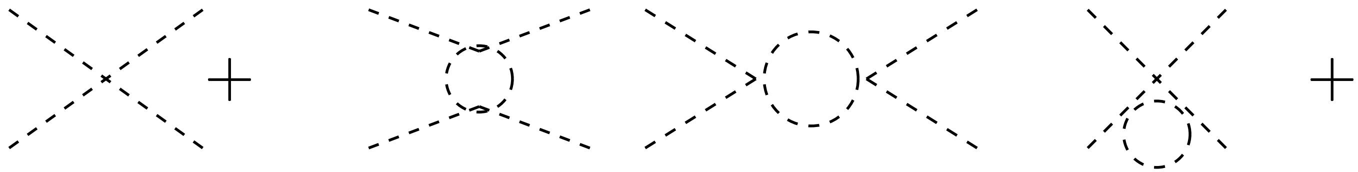
For a very heavy or no Higgs boson, we have: $a_0 \xrightarrow{s \ll M_H^2} -\frac{s}{32\pi v^2}$

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

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

2. Constraints on M_H: triviality

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



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

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

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

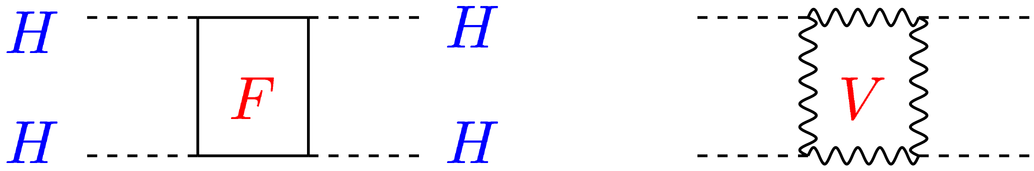
The SM is valid only at scales before λ becomes infinite:

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

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

2. Constraints on M_H: vacuum stability

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



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 the EW vacuum is instable.

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

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

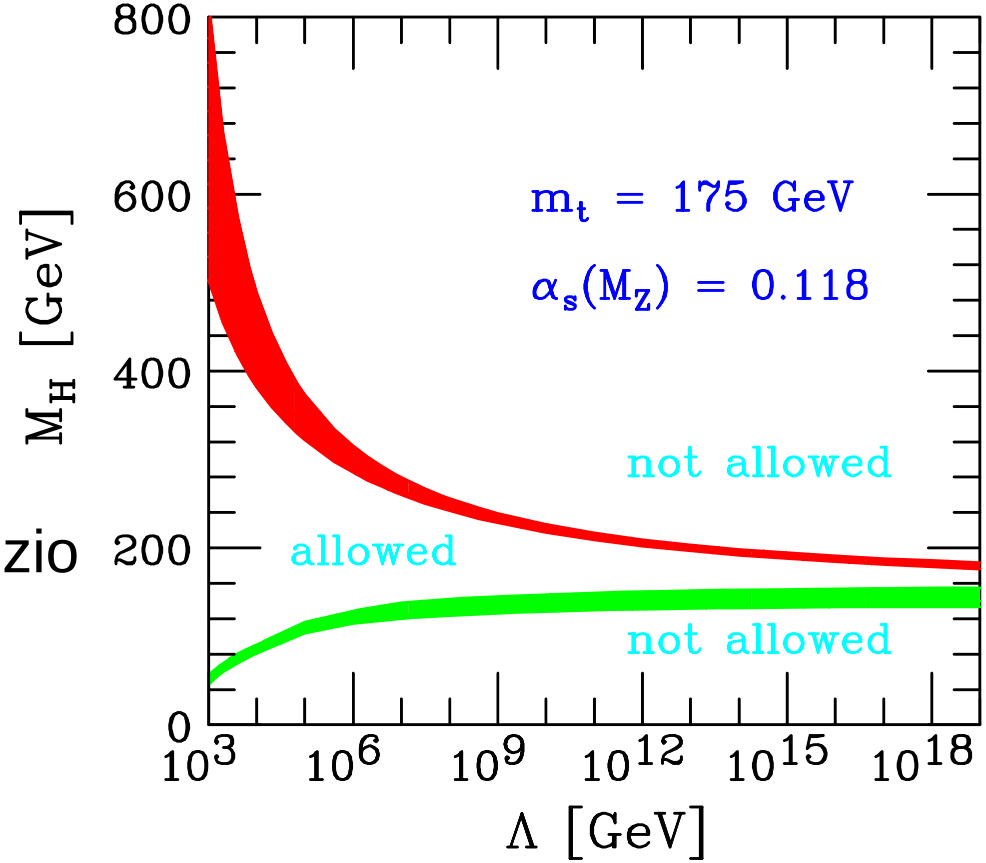
Very strong constraint: $Q = \Lambda_C \sim 1$ TeV $\Rightarrow M_H \gtrsim 70$ GeV

2. Constraints on M_H: triviality+stability

Combine the two constraints and include all possible effects:

- **– corrections at two loops**
- **– theoretical errors**
- **– experimental errors**
- **– other refinements $\cdots$**

Cabibbo, Maiani, Parisi, Petronzio
Hambye, Riesselmann



$$\Lambda_C \sim 10^3 \text{ GeV} \quad \Rightarrow \quad 70 \text{ GeV} \lesssim M_H \lesssim 700 \text{ GeV}$$

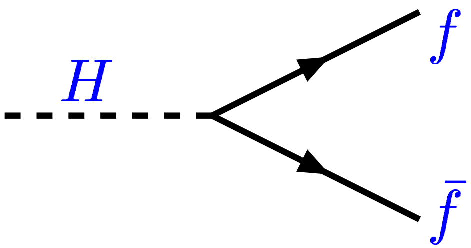
$$\Lambda_C \sim 10^{16} \text{ GeV} \quad \Rightarrow \quad 130 \text{ GeV} \lesssim M_H \lesssim 180 \text{ GeV}$$

3. Higgs decays

Higgs couplings proportional to particle masses: once M_H is fixed,

- **the profile of the Higgs boson is determined and its decays fixed,**
- **the Higgs has tendancy to decay into heaviest available particle.**

Higgs decays into fermions:



$$\Gamma_{\rm Born}(H \to f\bar{f}) = \frac{G_\mu N_c}{4\sqrt{2}\pi} M_H\, m_f^2\, \beta_f^3$$

$$\beta_f = \sqrt{1 - 4m_f^2/M_H^2} \;:\; \text{f velocity}$$

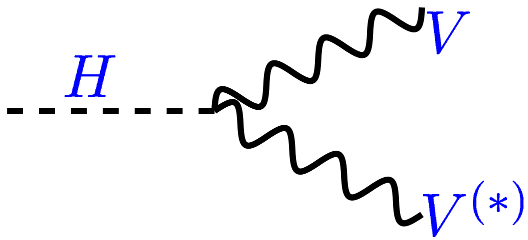
$$N_c = \text{color number}$$

- **Only $b\bar{b}, c\bar{c}, \tau^+\tau^-, \mu^+\mu^-$ for $M_H < 350$ GeV, also $t\bar{t}$ beyond.**
- **$\Gamma \propto \beta^3$: H is CP–even scalar particle ($\propto \beta$ for pseudoscalar H).**
- **Decay width grows as M_H: moderate growth....**
- **QCD RC: $\Gamma \propto \Gamma_0[1 - \frac{\alpha_s}{\pi} \log \frac{M_H^2}{m_q^2}] \Rightarrow$ very large: absorbed/summed**

using running masses at scale M_H : $m_b(M_H^2) \sim \frac{2}{3} m_b^{\rm pole} \sim 3\,{\rm GeV}$.

- **Include also direct QCD corrections (3 loops) and EW (one-loop).**

3. Higgs decays: decays into gauge bosons



$$\Gamma(H \to VV) = \frac{G_\mu M_H^3}{16\sqrt{2}\pi} \delta_V \beta_V \left(1 - 4x + 12x^2\right)$$

$$x = M_V^2/M_H^2,\ \beta_V = \sqrt{1-4x}$$

$$\delta_W = 2,\ \delta_Z = 1$$

- **For a very heavy Higgs boson:**

$\Gamma(H \to WW) = 2 \times \Gamma(H \to ZZ); \Rightarrow BR(WW) \sim \frac{2}{3}, BR(ZZ) \sim$

$\Gamma(H \to WW + ZZ) \propto \frac{1}{2} \frac{M_H^3}{(1\ \mathrm{TeV})^3}$ **because of contributions of V_L:**

heavy Higgs is obese: width very large, comparable to M_H at 1 TeV.

EW radiative corrections from scalars large because $\propto \lambda = \frac{M_H^2}{2v^2}$.

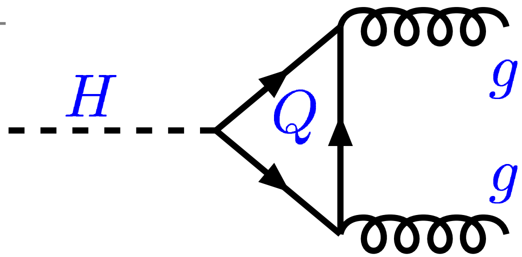
- **For a light Higgs boson:**

$M_H < 2M_V$: **possibility of off–shell V decays, $H \to VV^* \to Vf\bar{f}$.**

Virtuality and addition EW cplg compensated by large g_{HVV} vs g_{Hbb}.

In fact: for $M_H \gtrsim$ 130 GeV, $H \to WW^*$ dominates over $H \to b\bar{b}$

3. Higgs decays: decays into gluons



$$\Gamma\,(H \to gg) = \frac{G_\mu\,\alpha_s^2\,M_H^3}{36\,\sqrt{2}\,\pi^3}\left|\frac{3}{4}\sum_Q A_{1/2}^H(\tau_Q)\right|^2$$

$$A_{1/2}^H(\tau) = 2[\tau + (\tau - 1)f(\tau)]\,\tau^{-2}$$

$$f(\tau) = \arcsin^2\sqrt{\tau}\ \text{for}\ \tau = M_H^2/4m_Q^2 \leq 1$$

- Gluons massless and Higgs has no color: must be a loop decay.
- For $m_Q \to \infty, \tau_Q \sim 0 \Rightarrow A_{1/2} = \frac{4}{3} =$ constant and Γ is finite!

Width counts the number of strong inter. particles coupling to Higgs!

- In SM: only top quark loop relevant, b–loop contribution $\lesssim 5\%$.
- Loop decay but QCD and top couplings: comparable to cc, $\tau\tau$.
- Approximation $m_Q \to \infty/\tau_Q = 1$ valid for $M_H \lesssim 2m_t = 350$ GeV.

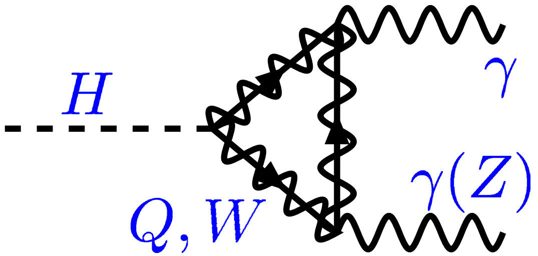
Good approximation in decay: include only t–loop with $m_Q \to \infty$. But:

- Very large QCD RC: the two– and three–loops have to be included:

$$\Gamma = \Gamma_0[1 + 18\frac{\alpha_s}{\pi} + 156\frac{\alpha_s^2}{\pi^2}] \sim \Gamma_0[1 + 0.7 + 0.3] \sim 2\Gamma_0$$

- Reverse process $gg \to H$ very important for Higgs production in pp!

3. Higgs decays: decays into photons



$$\Gamma = \frac{G_\mu \alpha^2 M_H^3}{128\sqrt{2}\pi^3}\left|\sum_f N_c e_f^2 A_{\frac{1}{2}}^H(\tau_f) + A_1^H(\tau_W)\right|^2$$

$$A_{1/2}^H(\tau) = 2[\tau + (\tau - 1)f(\tau)]\,\tau^{-2}$$

$$A_1^H(\tau) = -[2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)]\,\tau^{-2}$$

- **Photon massless and Higgs has no charge: must be a loop decay.**
- **In SM: only W–loop and top-loop are relevant (b–loop too small).**
- **For $m_i \to \infty \Rightarrow A_{1/2} = \frac{4}{3}$ and $A_1 = -7$: W loop dominating!**

(approximation $\tau_W \to 0$ valid only for $M_H \lesssim 2M_W$: relevant here!).

$\gamma\gamma$ width counts the number of charged particles coupling to Higgs!

- **Loop decay but EW couplings: very small compared to $H \to gg$.**
- **Rather small QCD (and EW) corrections: only of order $\frac{\alpha_s}{\pi} \sim 5\%$.**
- **Reverse process $\gamma\gamma \to H$ important for H production in $\gamma\gamma$.**
- **Same discussions hold qualitatively for loop decay $H \to Z\gamma$.**

3. Higgs decays: branching ratios

Branching ratios: $\mathrm{BR}(\mathrm{H} \to \mathrm{X}) \equiv \frac{\Gamma(\mathrm{H}\to\mathrm{X})}{\Gamma(\mathrm{H}\to\mathrm{all})}$

- **'Low mass range', $M_H \lesssim 130$ GeV:**

– $\mathrm{H} \to b\bar{b}$ **dominant, BR = 60–90%**

– $\mathrm{H} \to \tau^+\tau^-, c\bar{c}, gg$ **BR= a few %**

– $\mathrm{H} \to \gamma\gamma, \gamma Z$, **BR = a few permille.**

- **'High mass range', $M_H \gtrsim 130$ GeV:**

– $\mathrm{H} \to WW^*, ZZ^*$ **up to** $\gtrsim 2M_W$

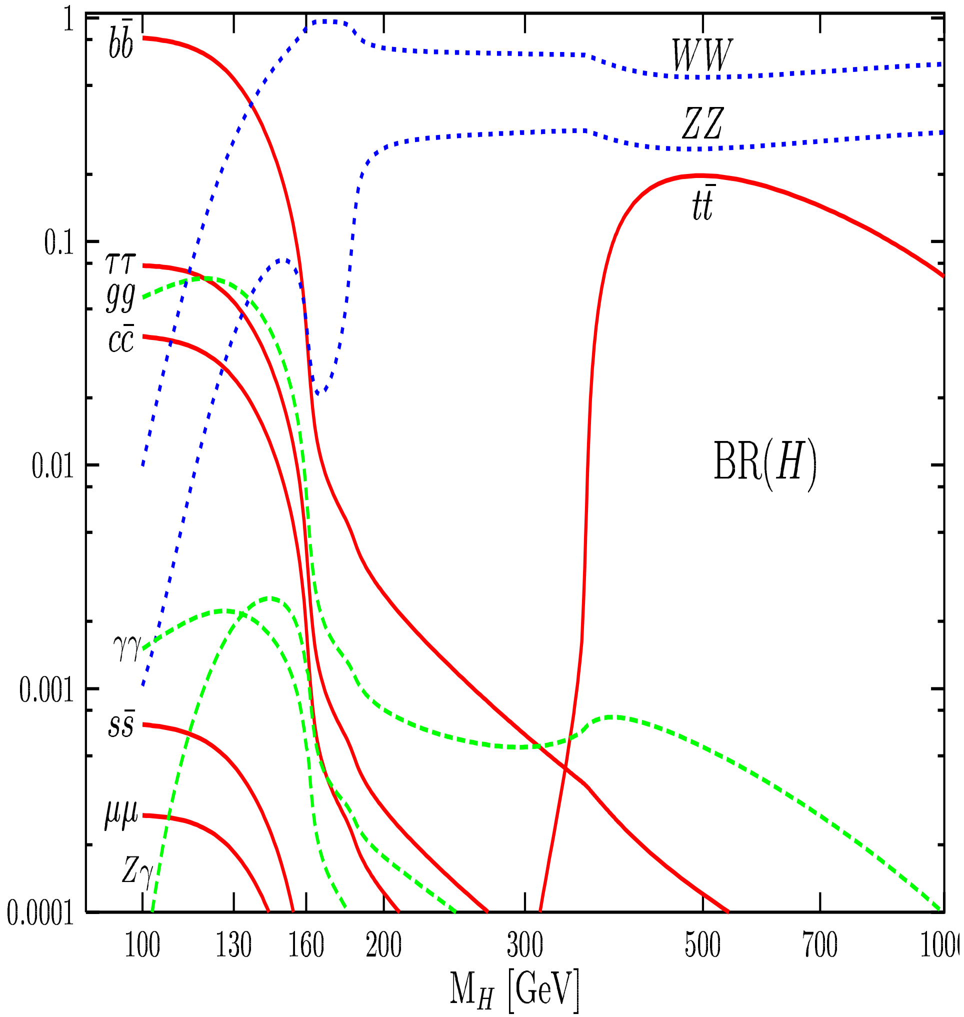
– $\mathrm{H} \to WW, ZZ$ **above (BR** $\to \frac{2}{3}, \frac{1}{3}$**)**

– $\mathrm{H} \to t\bar{t}$ **for high** M_H**; BR** $\lesssim 20\%$.

- **Total Higgs decay width:**

– $\mathcal{O}$**(MeV) for** $M_H \sim 100$ **GeV (small)**

– $\mathcal{O}$**(TeV) for** $M_H \sim 1$ **TeV (obese).**



3. Higgs decays: total width

Total decay width: $\Gamma_H \equiv \sum_X \Gamma(H \to X)$

- 'Low mass range', $M_H \lesssim 130$ GeV:
  - $H \to b\bar{b}$ dominant, BR = 60–90%
  - $H \to \tau^+\tau^-, c\bar{c}, gg$ BR= a few %
  - $H \to \gamma\gamma, \gamma Z$, BR = a few permille.
- 'High mass range', $M_H \gtrsim 130$ GeV:
  - $H \to WW^*, ZZ^*$ up to $\gtrsim 2M_W$
  - $H \to WW, ZZ$ above (BR $\to \frac{2}{3}, \frac{1}{3}$)
  - $H \to t\bar{t}$ for high M_H; BR $\lesssim 20\%$.
- Total Higgs decay width:
  - $\mathcal{O}$(MeV) for $M_H \sim 100$ GeV (small)
  - $\mathcal{O}$(TeV) for $M_H \sim 1$ TeV (obese).