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

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

The Lagrangian of the theory is given by:

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

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

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

1. The Standard Model: brief introduction

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

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

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

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

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

There is no ν_R **(and neutrinos are and stay exactly massless)**

– mediated by the W_μ^i **(isospin) and** B_μ **(hypercharge) gauge bosons**

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

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

Lagrangian simple: with fields strengths and covariant derivatives

$$W_{\mu\nu}^a = \partial_\mu W_\nu^a - \partial_\nu W_\mu^a + g_2 \epsilon^{abc} W_\mu^b W_\nu^c, \; B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

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

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

1. The Standard Model: brief introduction

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

$\frac{1}{2}{\rm M_V^2 V^\mu V_\mu}$ **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:

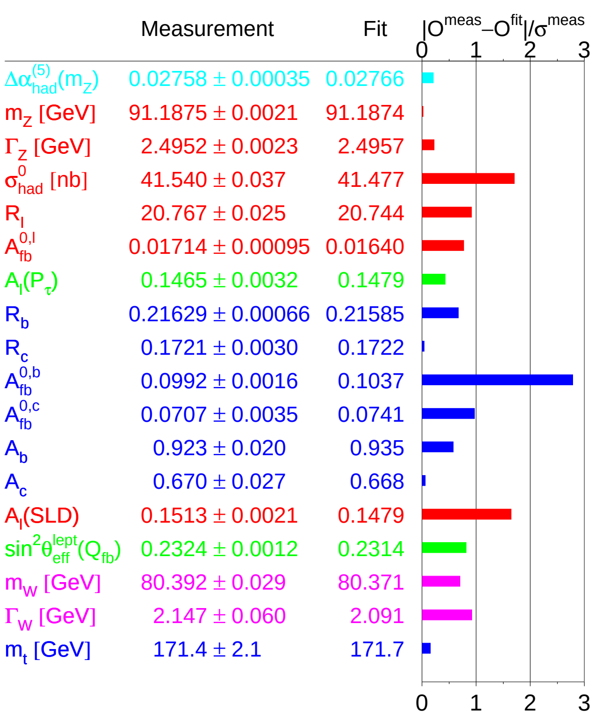
$\Rightarrow$ **The Brout-Englert-Higgs mechanism** $\Rightarrow$ **the Higgs particle H.**

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!

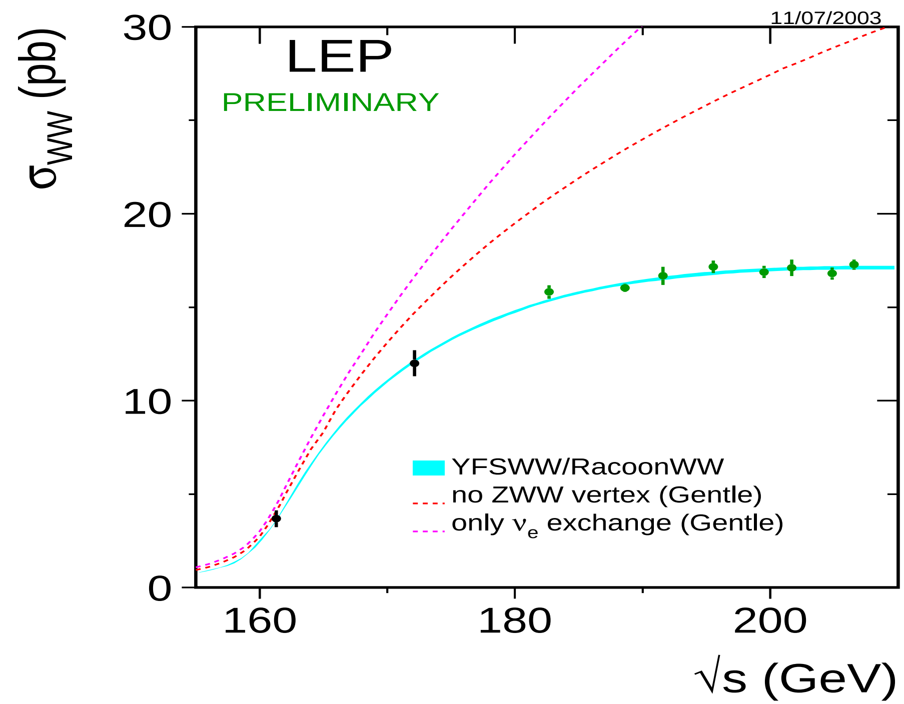
- **Couplings of fermions to γ,Z**
- **Z,W boson properties**
- **measure/running of α_S**



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

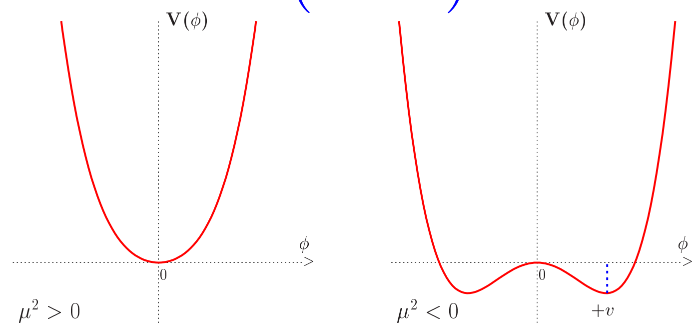
In the SM, if gauge boson and fermion masses are put by hand in $\mathcal{L}_{\rm SM}$

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 $SU(2)_L \times U(1)_Y$

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



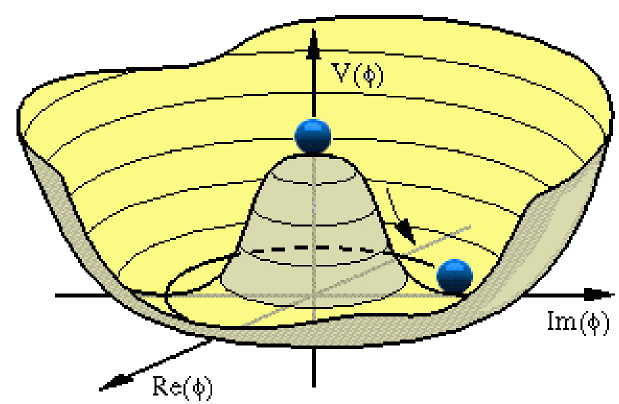
$\mu^2 > 0$: **4 scalar particles.**

$\mu^2 < 0$: 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 $\mathcal{L}_S$:

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

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

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

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

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

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

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

- For fermion masses, use <u>same</u> doublet field Φ and its <u>conjugate</u> 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?

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:

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

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

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

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

$$\Rightarrow g_{Hff} = i m_f/v \,, \; g_{HVV} = -2i M_V^2/v \,, \; g_{HHVV} = -2i M_V^2/v^2$$

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

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

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

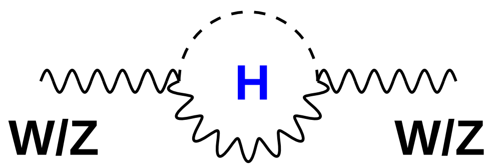
$$V = \frac{M_H^2}{2v}(H^2 + w_0^2 + 2w^+w^-)H + \frac{M_H^2}{8v^2}(H^2 + w_0^2 + 2w^+w^-)^2$$

3. Constraints on M_H

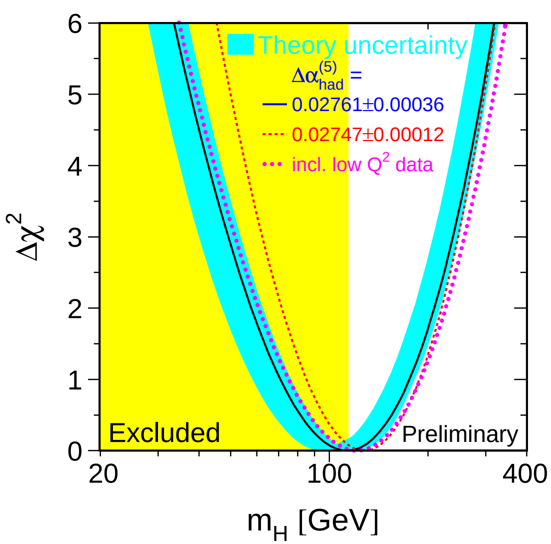
First, there were constraints from pre–LHC experiments....

Indirect Higgs searches:

H contributes to RC to W/Z masses:



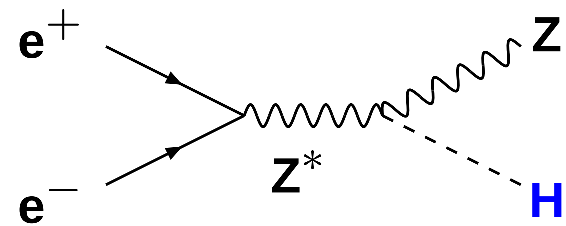
Fit the EW precision measurements:
we obtain $M_H = 92^{+34}_{-26}$ GeV, or



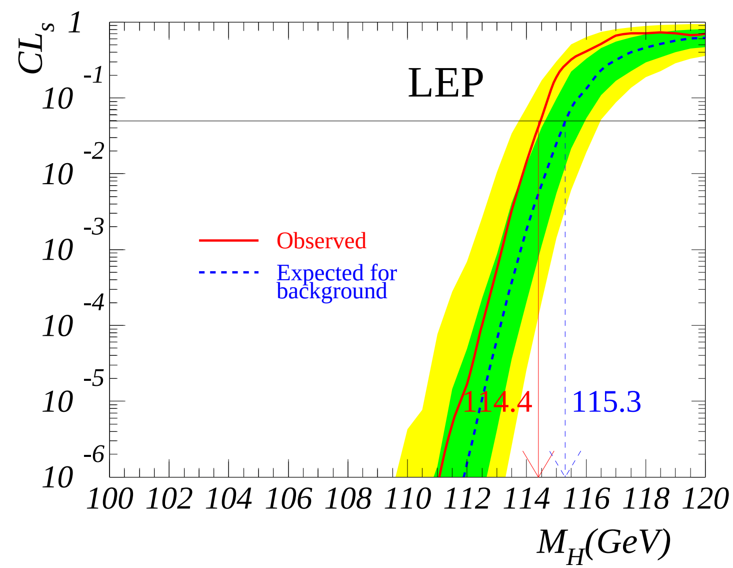
$M_H \lesssim 160$ GeV at 95% CL

Direct searches at colliders:

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



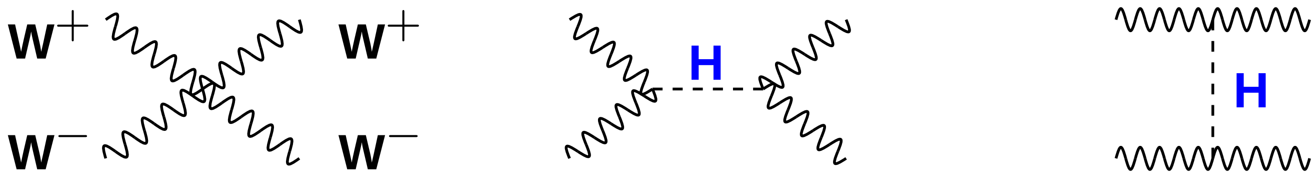
$M_H > 114.4$ GeV @95%CL



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: $a_0 \xrightarrow{s \gg M_H^2} -\frac{M_H^2}{8\pi v^2}$**

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

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

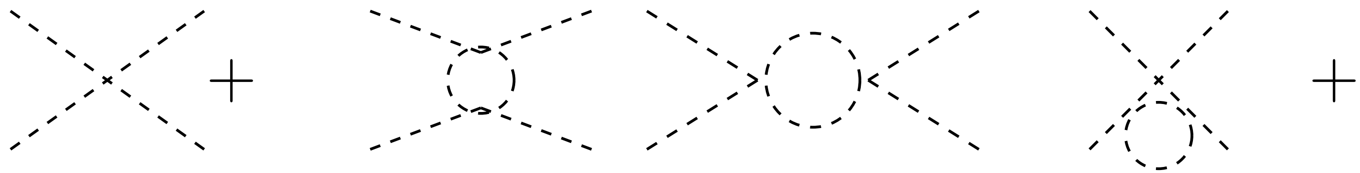
$$\text{unitarity} \Rightarrow \sqrt{s} \lesssim 1.7\ \text{TeV} \quad (\sqrt{s} \lesssim 1.2\ \text{TeV})$$

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

3. Constraints on $\mathrm{M_H}$: triviality

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

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



The RGE evolution of λ with $\mathrm{Q^2}$ and its solution are given by:

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

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

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

If $\Lambda_\mathrm{C} = \mathrm{M_H},\ \lambda \lesssim 4\pi \Rightarrow \mathrm{M_H} \lesssim 650$ GeV

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

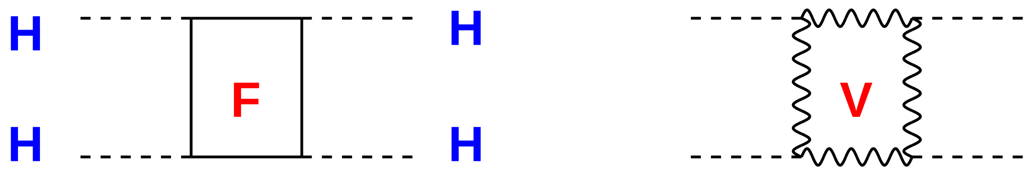
If $\Lambda_\mathrm{C} = \mathrm{M_P},\ \lambda \lesssim 4\pi \Rightarrow \mathrm{M_H} \lesssim 180$ GeV

(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

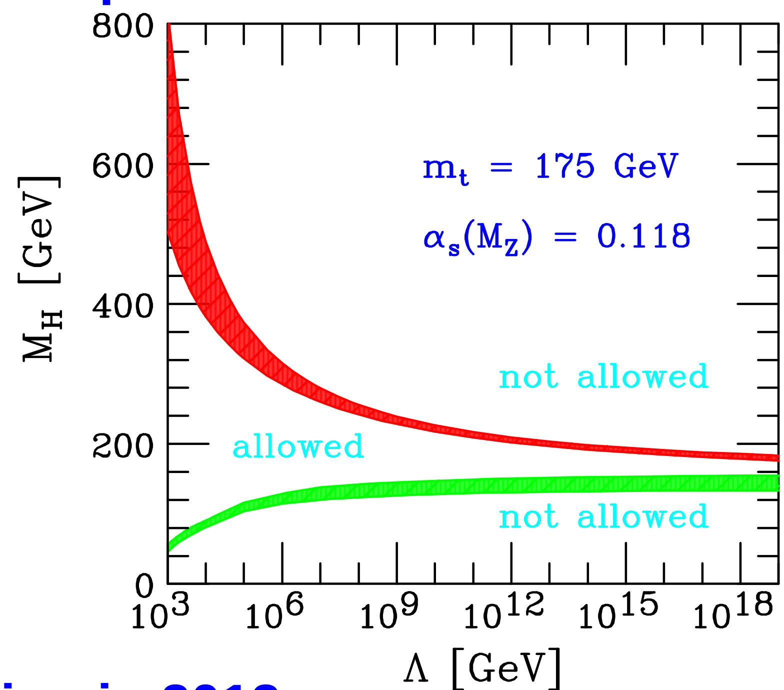
– other refinements $\cdots$

$\Lambda_C \approx 1$ 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.

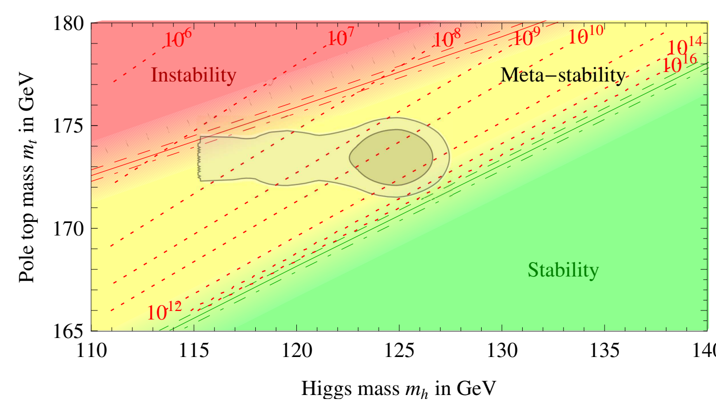
At 2–loop for m_t^{pole}=173.1 GeV:

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

but vacuum metastable below!

metastability OK: unstable vacuum

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

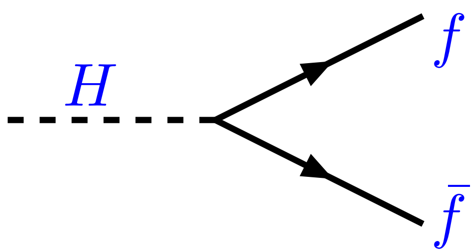


4. Higgs decays

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:



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

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

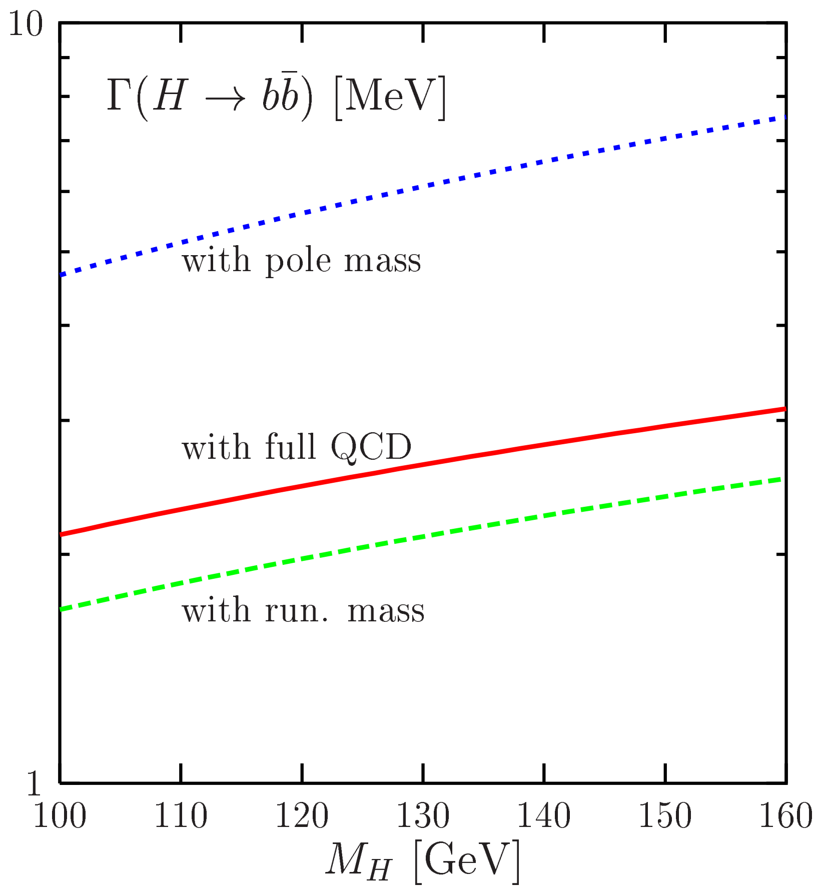
$$N_c = \text{color number}$$

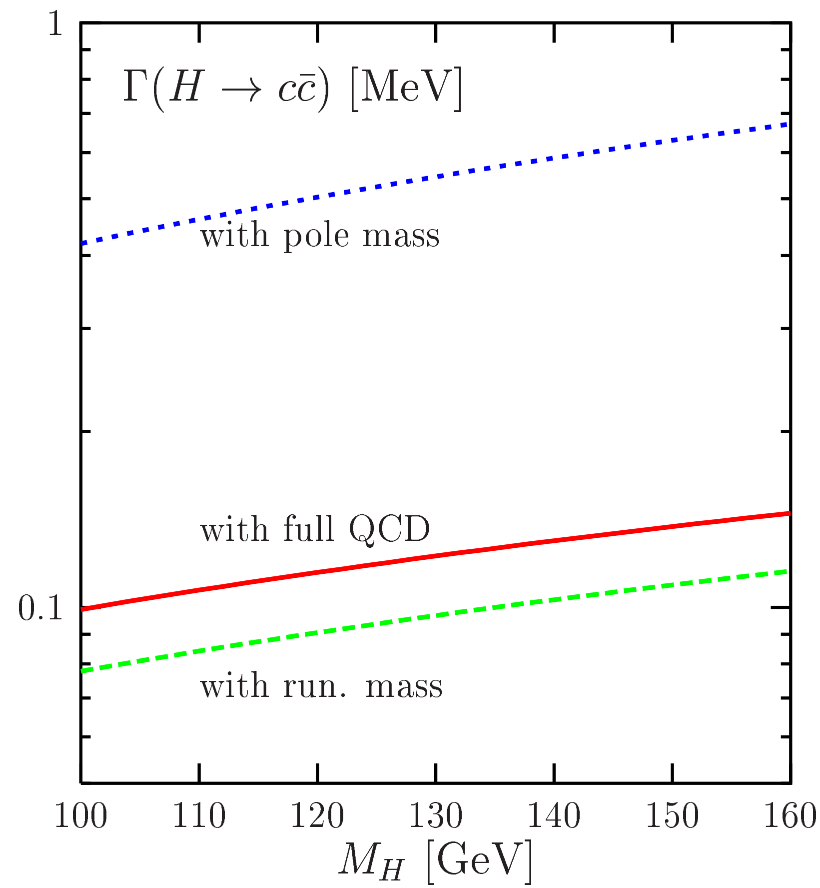
- **Only $b\bar{b}, c\bar{c}, \tau^+\tau^-, \mu^+\mu^-$ for $M_H < 350$ GeV, also $t\bar{t}$ beyond.**
- **$\Gamma \propto \beta^3$: H is CP–even scalar particle ($\propto \beta$ for pseudoscalar H).**
- **Decay width grows as M_H: moderate growth....**
- **QCD RC: $\Gamma \propto \Gamma_0[1 - \frac{\alpha_s}{\pi}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

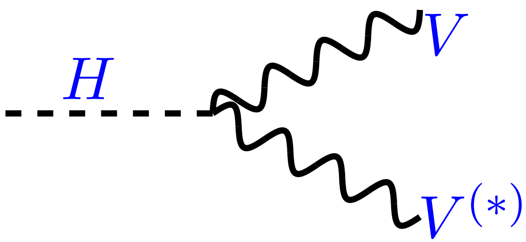
4. Higgs decays: QCD corrections





Partial widths for the decays $\mathrm{H \to b\bar{b}}$ and $\mathrm{H \to c\bar{c}}$ as a function of $\mathrm{M_H}$.

4. 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:**

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

$\Gamma(H \to WW + ZZ) \propto \frac{1}{2} \frac{M_H^3}{(1\ \text{TeV})^3}$ **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** $H \to b\bar{b}$

4. Higgs decays: decays into gauge bosons

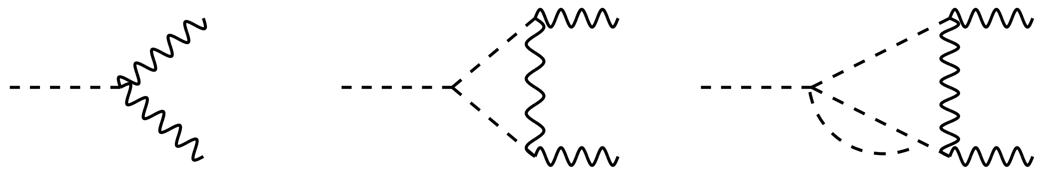
Electroweak radiative corrections to $\mathbf{H \to VV}$:

Using the low–energy/equivalence theorem for $\mathbf{M_H \gg M_V}$, Born easy..

$$\Gamma(\mathrm{H\to ZZ}) \sim_! \Gamma(\mathrm{H \to w_0 w_0}) = \left(\frac{1}{2M_H}\right)\left(\frac{2!M_H^2}{2v}\right)^2 \frac{1}{2}\left(\frac{1}{8\pi}\right) \to \frac{M_H^3}{32\pi v^2}$$

$\mathbf{H \to WW}$: remove statistical factor: $\Gamma(\mathrm{H \to W^+W^-}) \simeq 2\Gamma(\mathrm{H \to ZZ})$.

Include now the one– and two–loop EW corrections from H/W/Z only:



$$\Gamma_{\mathrm{H\to VV}} \simeq \Gamma_{\mathrm{Born}}\left[1 + 3\hat{\lambda} + 62\hat{\lambda}^2 + \mathcal{O}(\hat{\lambda}^3)\right] \;\; ; \quad \hat{\lambda} = \lambda/(16\pi^2)$$

$\mathbf{M_H \sim \mathcal{O}(10\ TeV)} \Rightarrow$ one–loop term = Born term.

$\mathbf{M_H \sim \mathcal{O}(1\ TeV)} \Rightarrow$ one–loop term = two–loop term

$\Rightarrow$ for perturbation theory to hold, one should have $\mathbf{M_H \lesssim 1}$ TeV.

Approx. same result from the calculation of the fermionic Higgs decays:

$$\Gamma_{\mathrm{H\to ff}} \simeq \Gamma_{\mathrm{Born}}\left[1 + 2\hat{\lambda} - 32\hat{\lambda}^2 + \mathcal{O}(\hat{\lambda}^3)\right]$$

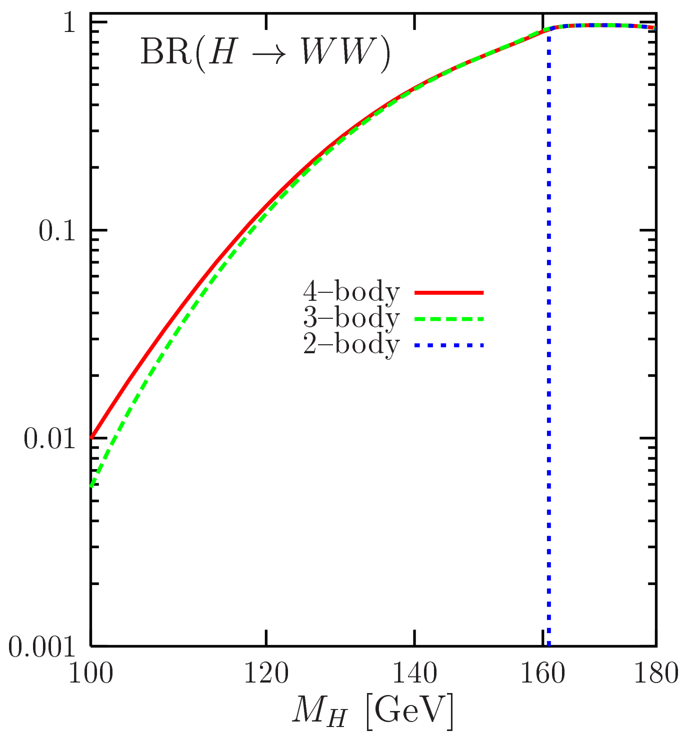
4. Higgs decays: decays into gauge bosons

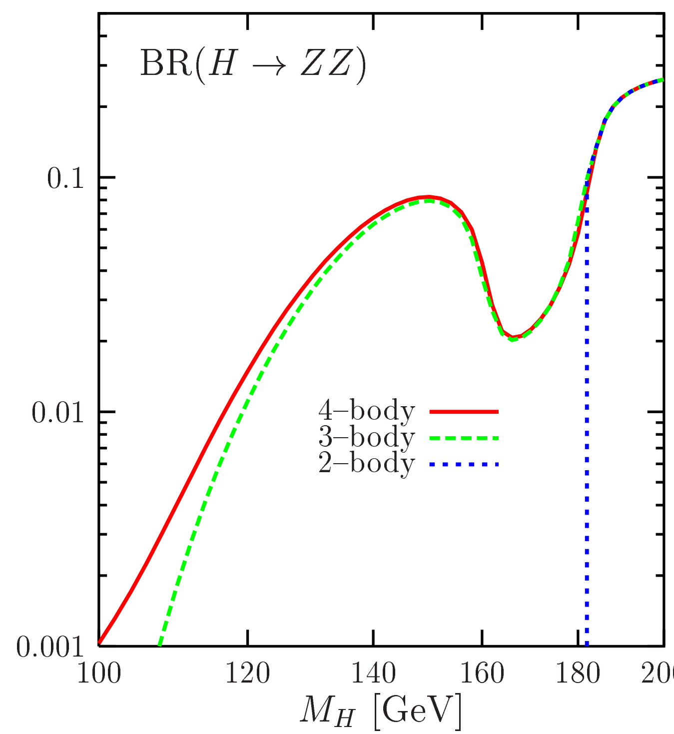
gd 2+3+4 body decay calculation of $\mathbf{H \to V^* V^*}$:

$$\mathbf{\Gamma(H \to V^* V^*) = \frac{1}{\pi^2} \int_0^{M_H^2} \frac{dq_1^2 M_V \Gamma_V}{(q_1^2 - M_V^2)^2 + M_V^2 \Gamma_V^2} \int_0^{(M_H - q_1)^2} \frac{dq_2^2 M_V \Gamma_V}{(q_2^2 - M_V^2)^2 + M_V^2 \Gamma_V^2} \Gamma_0}$$

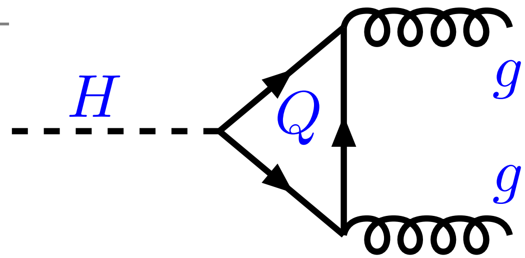
$\mathbf{\lambda(x, y; z) = (1 - x/z - y/z)^2 - 4xy/z^2}$ **with** $\mathbf{\delta_{W/Z} = 2/1}$ **and**

$$\mathbf{\Gamma_0 = \frac{G_\mu M_H^3}{16\sqrt{2}\pi} \delta_V \sqrt{\lambda(q_1^2, q_2^2; M_H^2)} \left[\lambda(q_1^2, q_2^2; M_H^2) + \frac{12 q_1^2 q_2^2}{M_H^4} \right]}$$





4. 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.

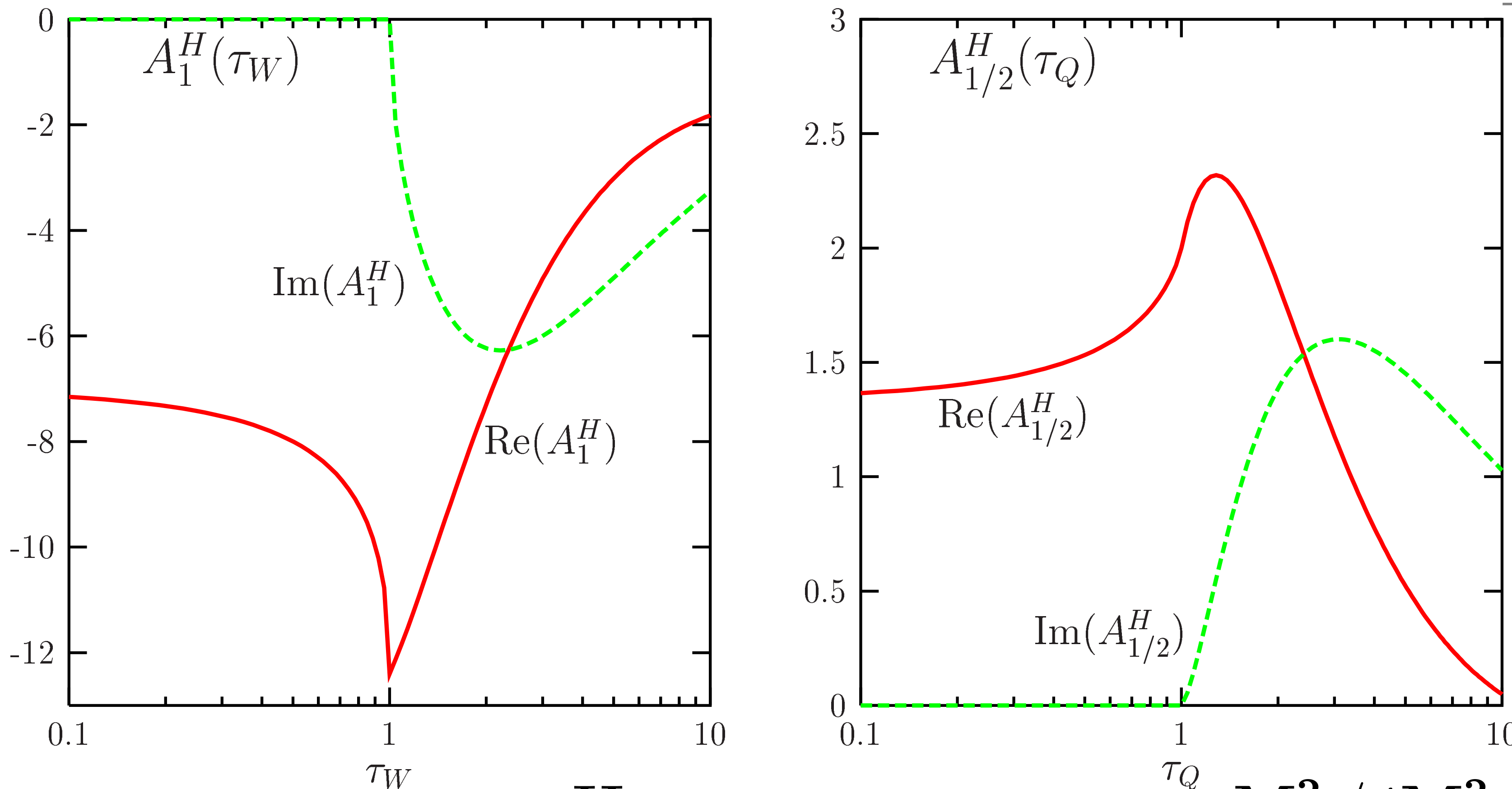
Good approximation in decay: include only t–loop with $m_Q \to \infty$. But:

- 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!

4. Higgs decays: loop form factors

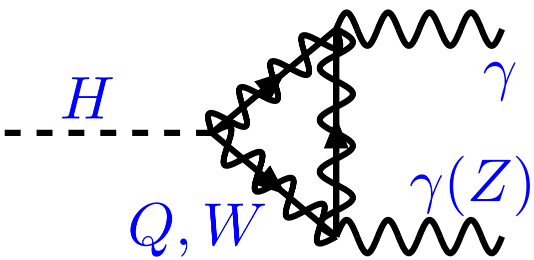


W and fermion amplitudes in $H \to \gamma\gamma$ as function of $\tau_i = M_H^2/4M_i^2$.

We could repeat the calculation of $H \to \gamma\gamma$ and check that Barroso+ Pulido+Romao (1986) and Higgs Hunters Guide were correct??...

Trick for an easy calculation: low energy theorem for $M_H \ll Mi$....

4. 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 $H \to Z\gamma$.**

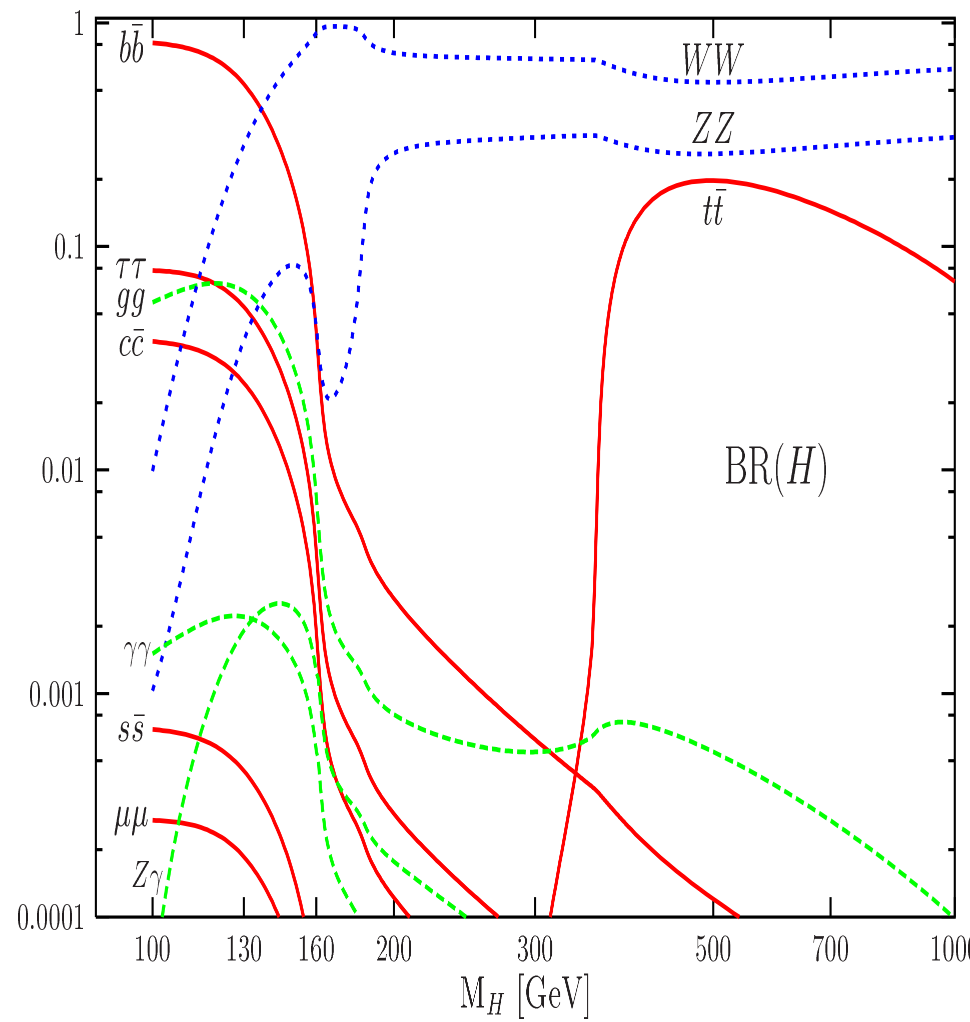
4. Higgs decays: branching ratios

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:**
- – $H \to b\bar{b}$ **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).**



4. 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:**
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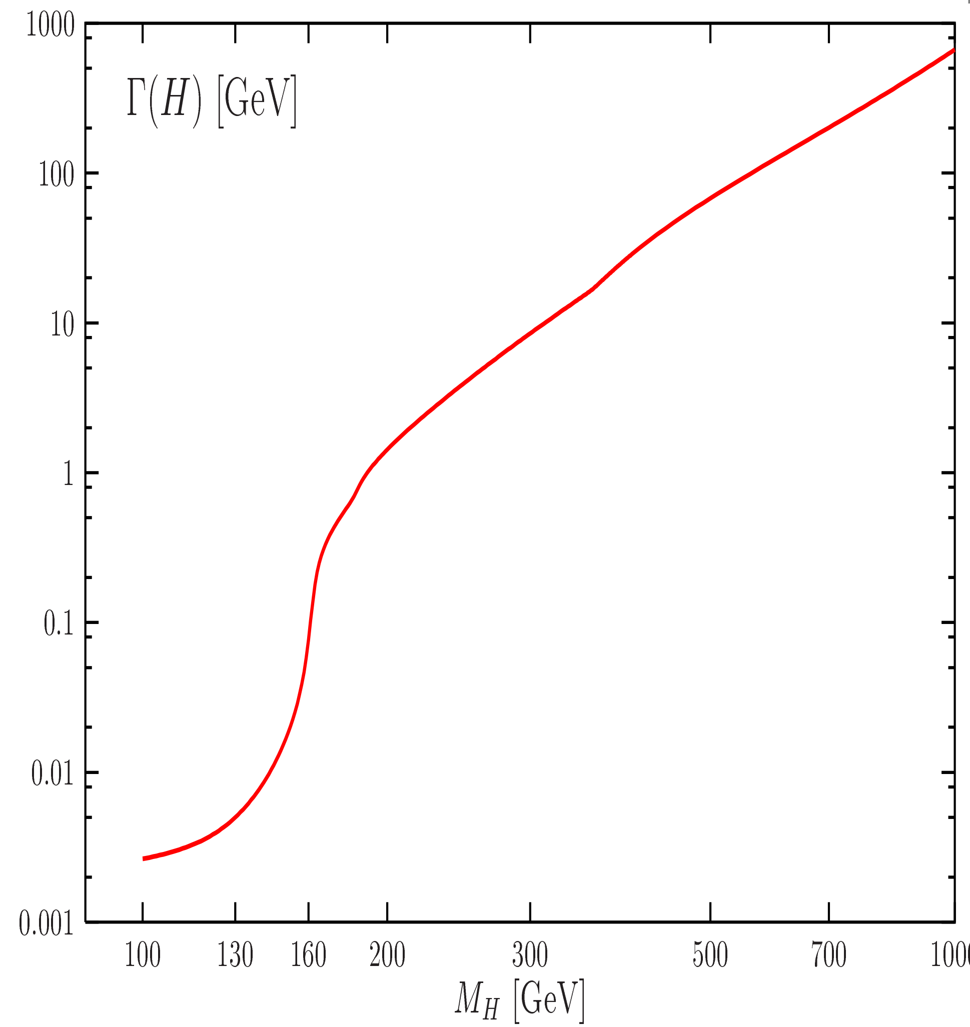


4. Higgs decays: theory uncertainties

However: there are theoretical uncertainties....

- **Input quark masses in** $H \to b\bar{b}, c\bar{c}$

$$M_Q^{\rm pole} \to \overline{m}_Q(\mu = M_H)$$

– $\overline{m}_b(M_b) = 4.19^{+0.018}_{-0.006}$ **GeV**

– $\overline{m}_c(M_c) = 1.27^{+0.007}_{-0.009}$ **GeV**

- **Theory+experimental error on** α_s **:**

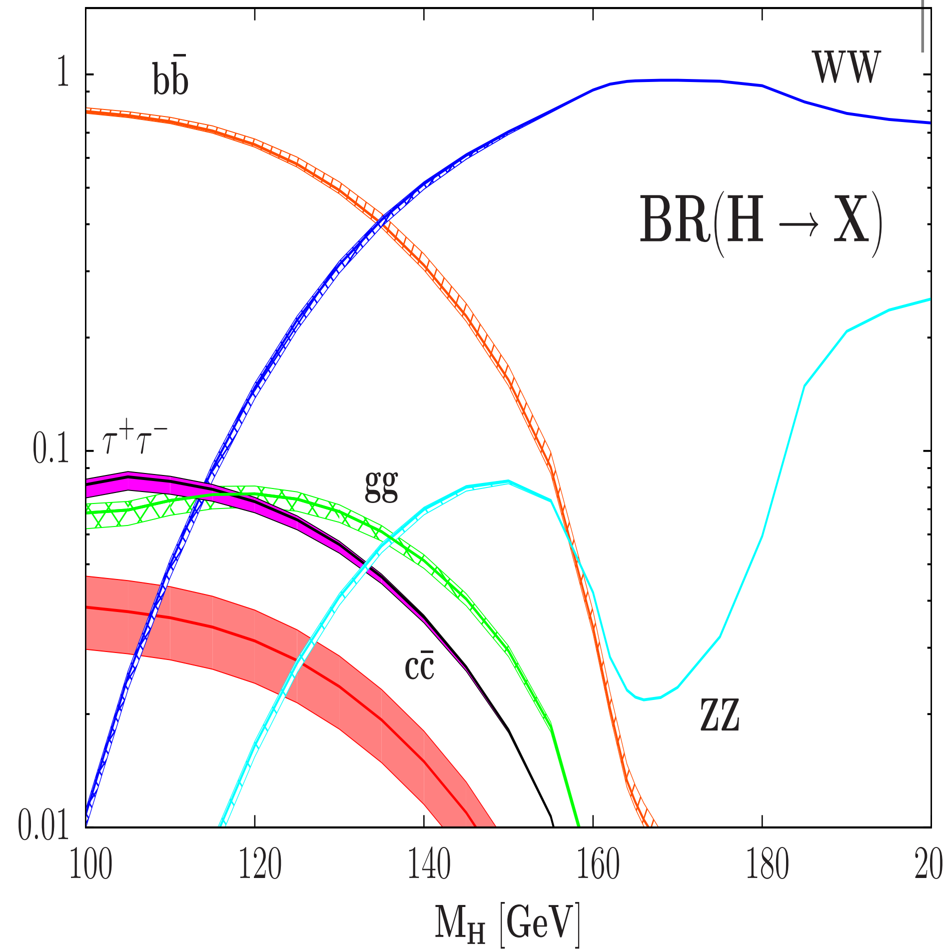
$\alpha_s(M_Z^2) = 0.1171 \pm 0.0014$ **@NNLO**

- **Scale error: measure of higher orders**

$$\tfrac{1}{2}M_H \le \mu \le 2M_H$$

- **Scale and** α_s **errors in** $H \to gg$

$\Gamma(H \to gg) \propto \alpha_s^2 + \text{large } \mathcal{O}(\alpha_s^3)$



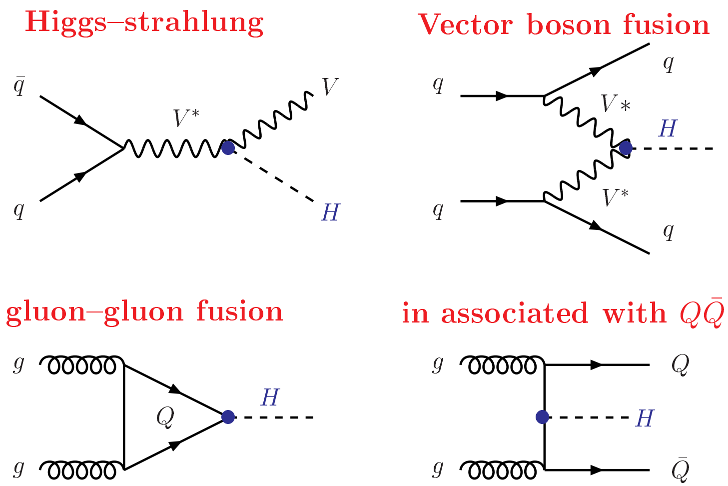
..

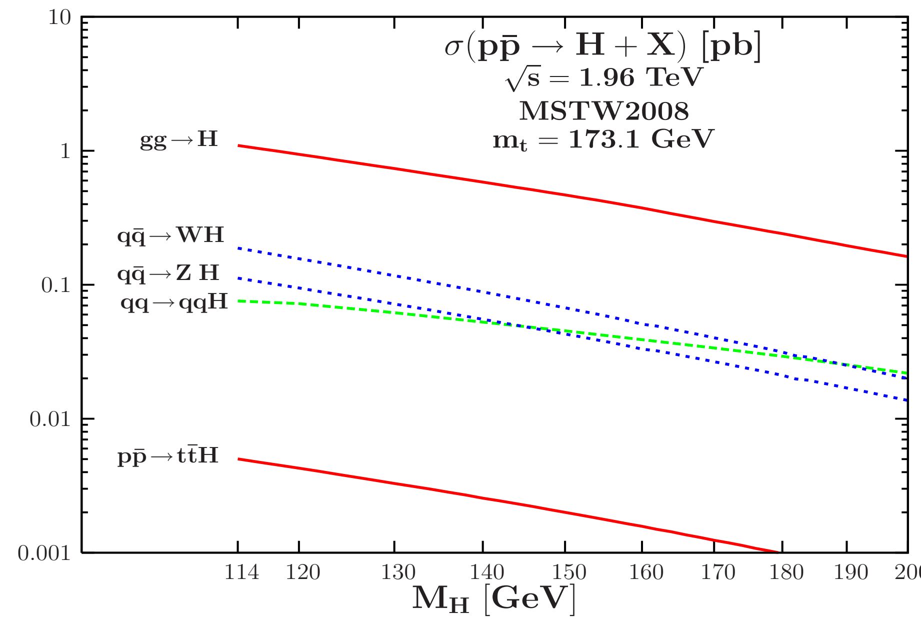
Include all items ⇒ non-negligible uncertainties.

esp. for $M_H \approx$**120–150 GeV: 5–10% for** $H \to b\bar{b}$ **and** $H \to WW^*$

5. SM Higgs at hadron colliders

Main Higgs production channels





Large production cross sections

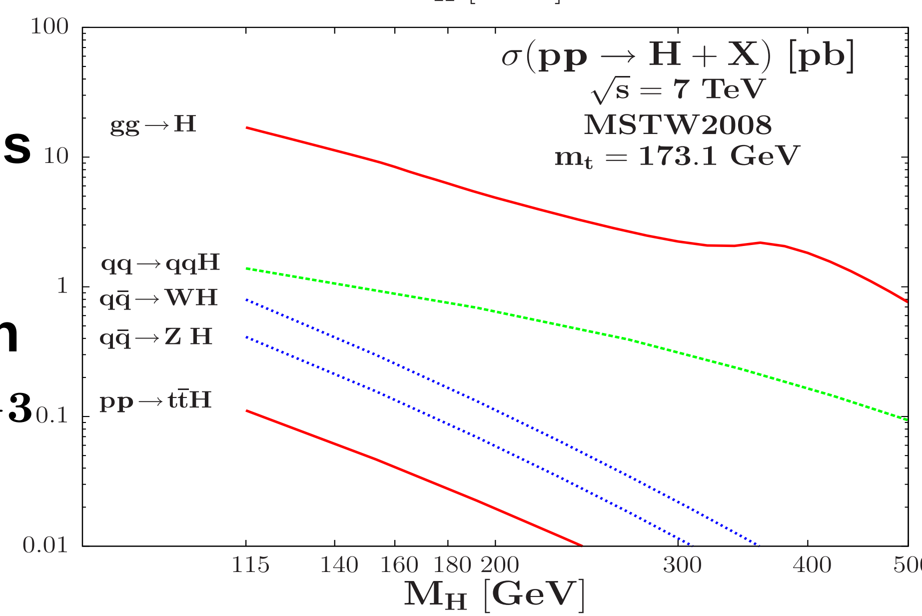
with gg→ H by far dominant process

1 $\text{fb}^{-1} \Rightarrow \mathcal{O}(10^4)$ events@lHC

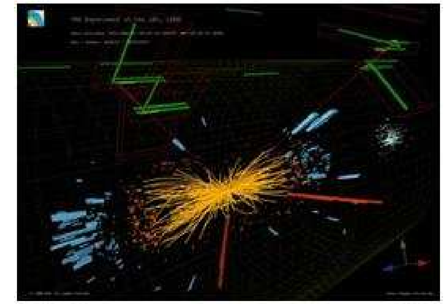
$\Rightarrow \mathcal{O}(10^3)$ events @Tevatron

but eg BR(H$\to \gamma\gamma, ZZ \to 4\ell) \approx 10^{-3}$

... a small # of events at the end...



5. SM Higgs at hadron colliders: generalities



⇒ **an extremely challenging task!**

- **Huge cross sections for QCD processes**
- **Small cross sections for EW Higgs signal**

  S/B $\gtrsim 10^{10}$ ⇒ a needle in a haystack!
- **Need some strong selection criteria:**

– trigger: get rid of uninteresting events...

– select clean channels: $H \to \gamma\gamma, VV \to \ell$

– use specific kinematic features of Higgs

- **Combine # decay/production channels**

(and eventually several experiments...)

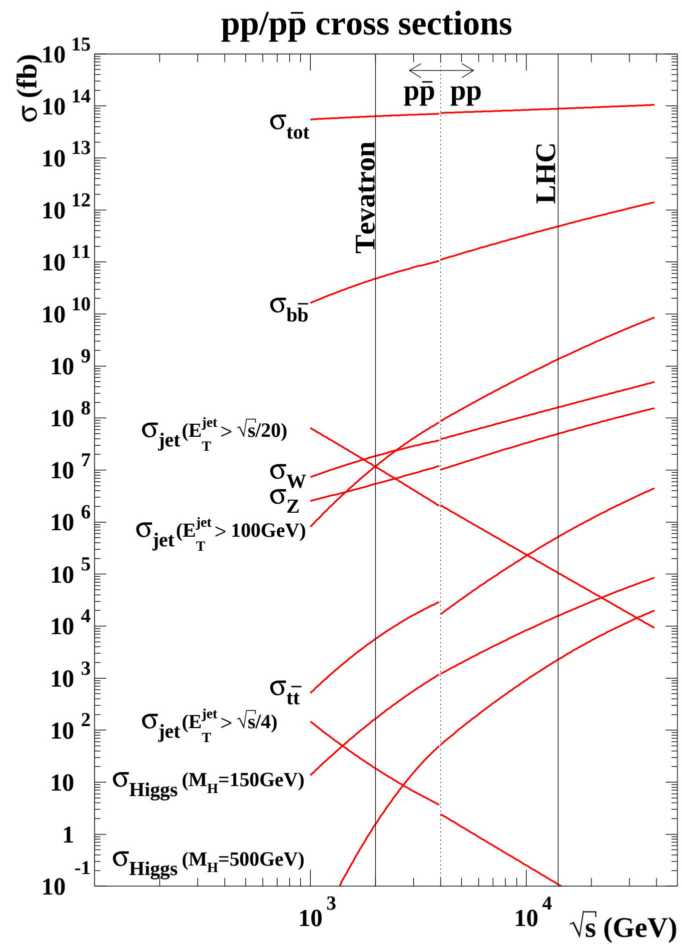
- **Have a precise knowledge of S and B rates**

(higher orders can be factor of 2! see later)

- **Gigantic experimental + theoretical efforts**

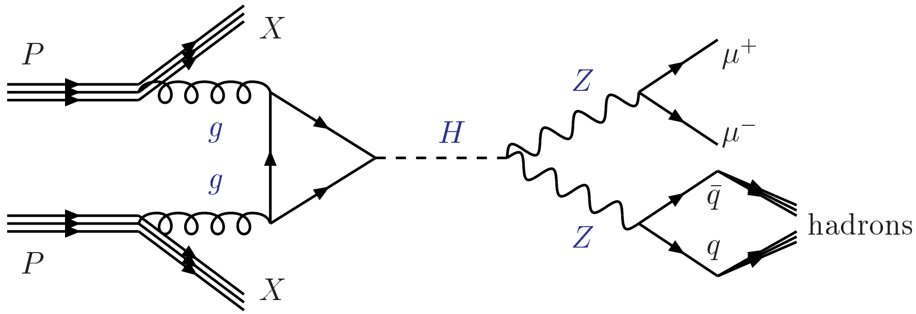
(more than 30 years of very hard work!)

For a flavor of how it is complicated from the theory side: a look at the $gg \to H$ case



5. SM Higgs at hadron colliders: generalities

Example of process at LHC to see how things work: $gg \to H$



$$N_{ev} = \mathcal{L} \times P(g/p) \times \hat{\sigma}(gg \to H) \times B(H \to ZZ) \times B(Z \to \mu\mu) \times BR(Z \to qq)$$

For a large number of events, all these numbers should be large!

Two ingredients: hard process (σ, B) and soft process (PDF, hadr).

Factorization theorem! Here discuss production/decay process.

The partonic cross section of the subprocess, $gg \to H$, is:

$$\hat{\sigma}(gg \to H) = \int \frac{1}{2\hat{s}} \times \frac{1}{2 \cdot 8} \times \frac{1}{2 \cdot 8} |\mathcal{M}_{Hgg}|^2 \frac{d^3 p_H}{(2\pi)^3 2E_H} (2\pi^4) \delta^4 (q - p_H)$$

Flux factor, color/spin average, matrix element squared, phase space.

Convolute with gluon densities to obtain total hadronic cross section

$$\sigma = \int_0^1 dx_1 \int_0^1 dx_2 \frac{\pi^2 M_H}{8\hat{s}} \Gamma(H \to gg) g(x_1) g(x_2) \delta(\hat{s} - M_H^2)$$

5. SM Higgs at hadron colliders: generalities

The calculation of $\sigma_{\rm born}$ is not enough in general at pp colliders:

need to include higher order radiative corrections which introduce terms of order $\alpha_{\rm s}^{\rm n} \log^{\rm m}({\rm Q}/{\rm M_H})$ where Q is either large or small...

- **Since α_s is large, these corrections are in general very important.**
- **Choose a (natural scale) which absorbs/resums the large logs.**

Since we truncate pert. series: only NLO/NNLO corrections available.

- **The (hope small) not known HO corrections induce a theoretical error.**
- **The scale variation is a (naive) measure of the HO: must be small.**

Also, precise knowledge of σ is not enough: need to calculate some kinematical distributions (e.g. ${\rm p_T}, \eta, \frac{{\rm d}\sigma}{{\rm dM}}$) to distinguish S from B.

In fact, one has to do this for both the signal and background (unless directly measurable from data): the important quantity is $\sigma = \frac{\rm N_S}{\sqrt{\rm N_{bjg}}}$

$\Rightarrow$ a lot of theoretical work is needed!

But most complicated thing is to actually see the signal for S/B$\ll$1!