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: $\Psi(\mathbf{x}) \to \Psi'(\mathbf{x}) = \mathbf{e}^{\mathbf{ie}\alpha(\mathbf{x})}\Psi(\mathbf{x})$

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

The Lagrangian density is invariant under above field transformations

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

field strength $\mathbf{F}_{\mu\nu} = \partial_\mu\mathbf{A}_\nu - \partial_\nu\mathbf{A}_\mu$ **and cov. derivative** $\mathbf{D}_\mu = \partial_\mu - \mathbf{ieA}_\mu$

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

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

- The group $SU(3)_C$ describes the strong force:

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

– mediated by 8 gluons, G_μ^a corresponding to 8 generators of $SU(3)_C$

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

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

The Lagrangian of the theory is given by:

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

with $G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f^{abc} G_\mu^b G_\nu^c$

The interactions/couplings are then uniquely determined:

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

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

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

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

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

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

1. The Standard Model: brief introduction

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

$\frac{1}{2}M_V^2 V^\mu V_\mu$ and/or $m_f \bar{f} f$ 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 $U(1)_Q$ local symmetry:

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

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

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

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

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

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

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

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

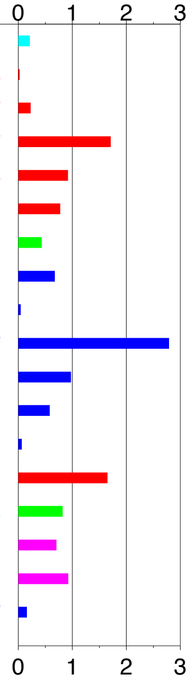
$\Rightarrow$ The Brout-Englert-Higgs mechanism $\Rightarrow$ the Higgs particle H.

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**

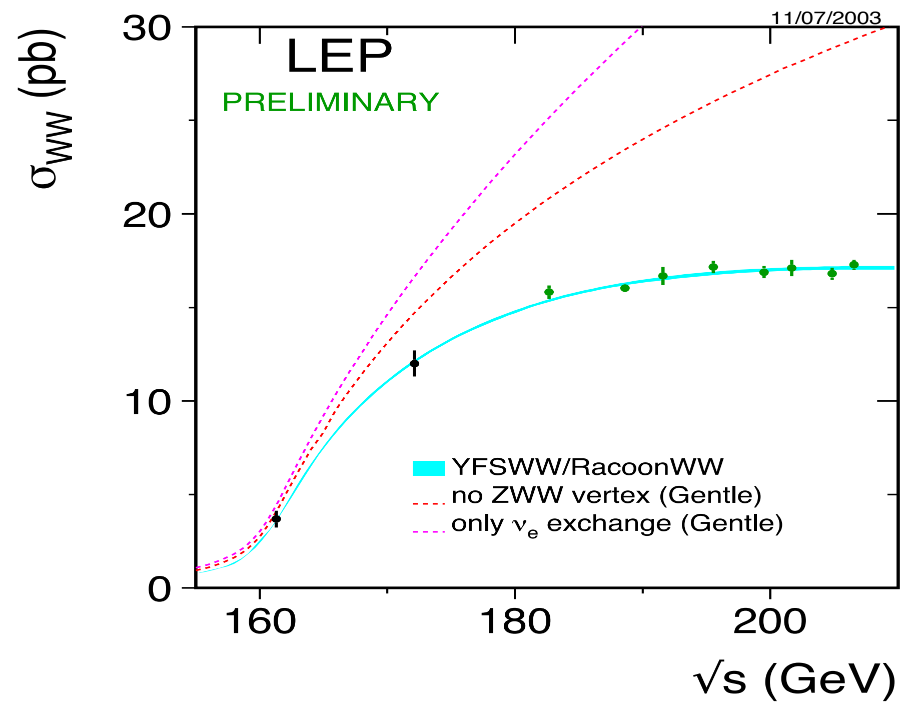


	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02766	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957	
σ^0_{had} [nb]	41.540 ± 0.037	41.477	
R_l	20.767 ± 0.025	20.744	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01640	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479	
R_b	0.21629 ± 0.00066	0.21585	
R_c	0.1721 ± 0.0030	0.1722	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0741	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1479	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.392 ± 0.029	80.371	
Γ_W [GeV]	2.147 ± 0.060	2.091	
m_t [GeV]	171.4 ± 2.1	171.7	

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.**

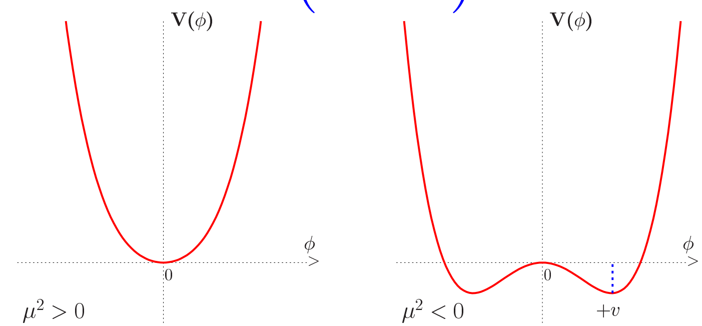
$\mu^2 < 0$: Φ **develops a vev:**

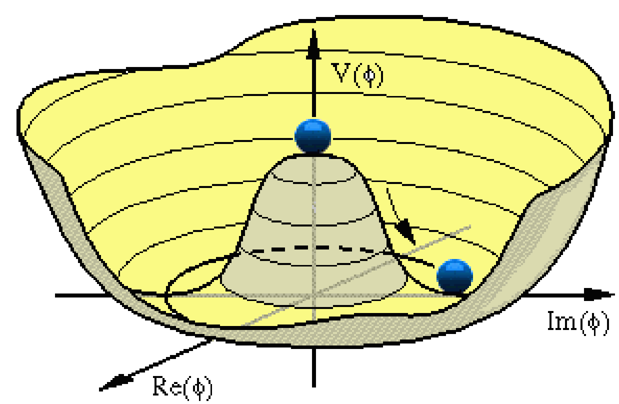
$$\langle 0|\Phi|0\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

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

– 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 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?

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:

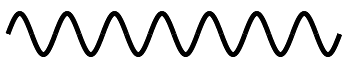
$$\mathcal{L}_{M_V} \sim M_V^2 (1 + H/v)^2 \;,\; \mathcal{L}_{m_f} \sim -m_f (1 + H/v)$$

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

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, $\mathrm{s}\gg \mathrm{M_V^2}$, an approximation is $\mathrm{M_V}\sim 0$. The $\mathrm{V_L}$ components of V can be replaced by the Goldstones, $\mathrm{V_L}\to\mathrm{w}$.**
- **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:

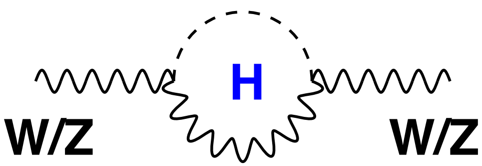
$$\mathbf{V=\frac{M_H^2}{2v}(H^2+w_0^2+2w^+w^-)H+\frac{M_H^2}{8v^2}(H^2+w_0^2+2w^+w^-)^2}$$

3. Constraints on M_H

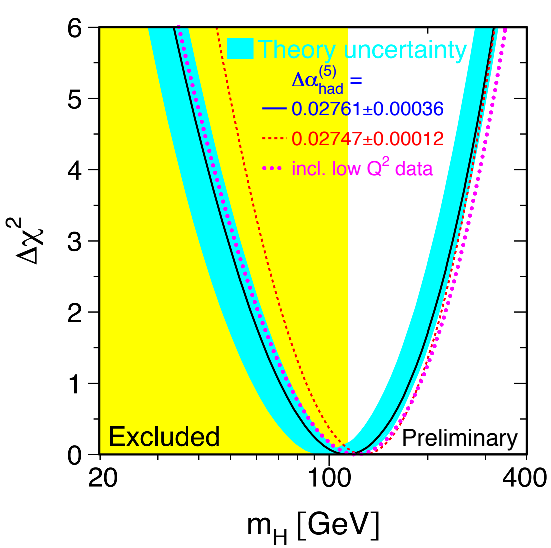
First, there were constraints from pre–LHC experiments....

Indirect Higgs searches:

H contributes to RC to W/Z masses:



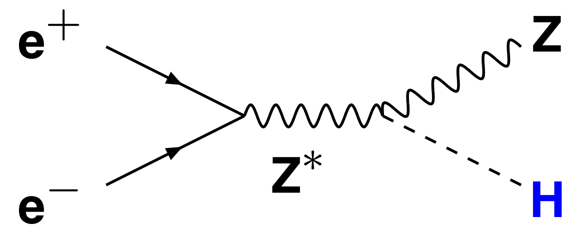
Fit the EW precision measurements:
we obtain $M_H = 92^{+34}_{-26}$ GeV, or



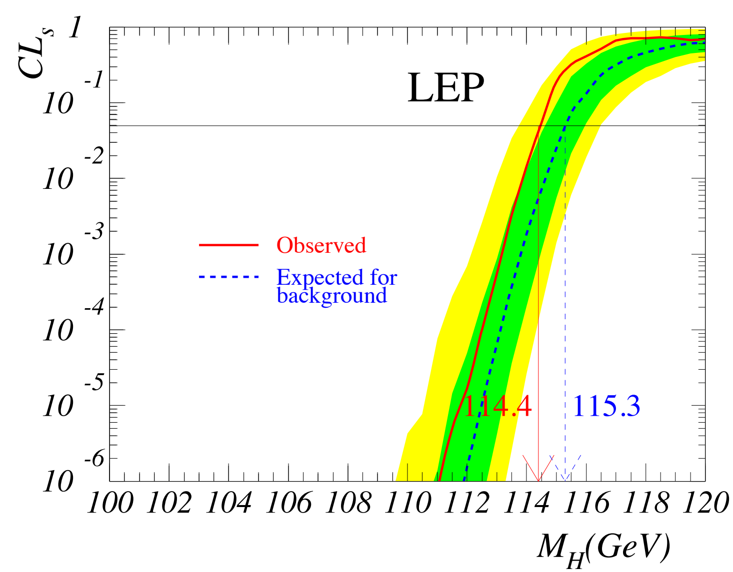
$M_H \lesssim 160$ GeV at 95% CL

Direct searches at colliders:

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



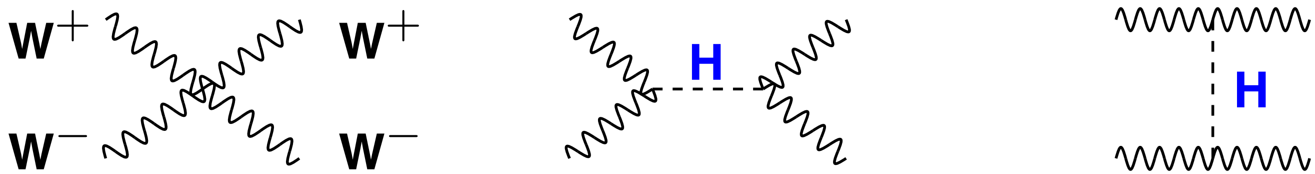
$M_H > 114.4$ GeV @95%CL



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

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

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

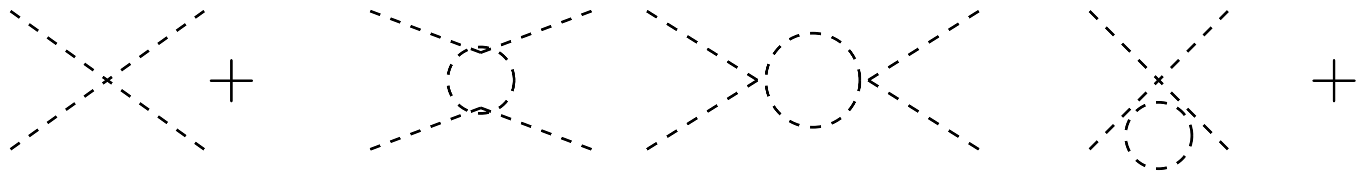
$$\text{unitarity} \Rightarrow \sqrt{s} \lesssim 1.7\ \text{TeV} \quad (\sqrt{s} \lesssim 1.2\ \text{TeV})$$

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

3. Constraints on 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

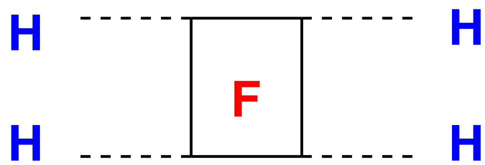
(comparable to results obtained with simulations on the lattice!)

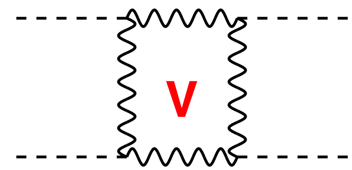
If $\Lambda_C = M_P,\ \lambda \lesssim 4\pi \Rightarrow M_H \lesssim 180$ GeV

(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

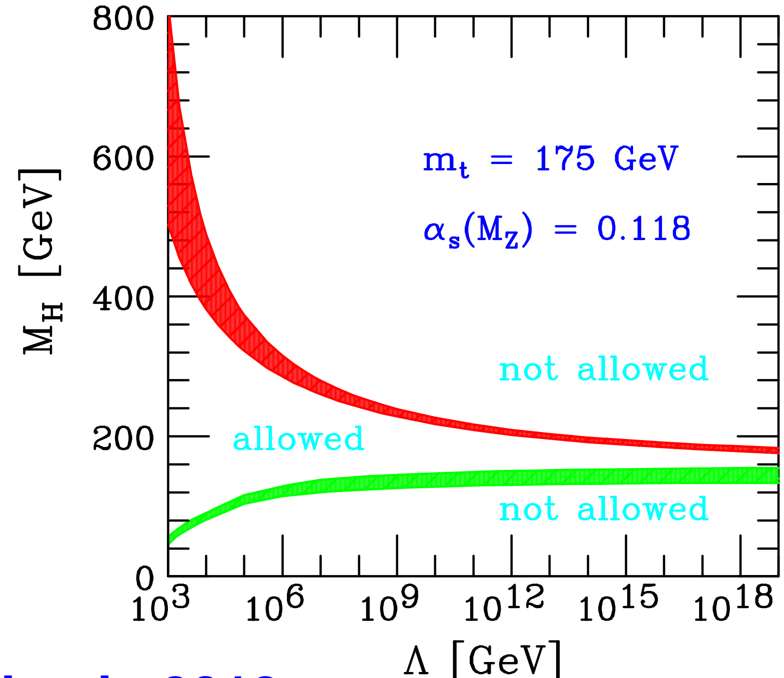
– other refinements $\cdots$

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

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

Cabibbo, Maiani, Parisi, Petronzio

Hambye, Riesselmann



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

Degrassi et al., Berzukov et al.

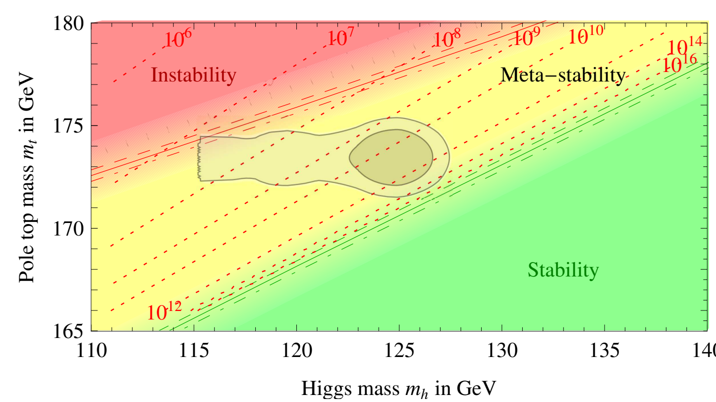
At 2–loop for $m_t^{\rm pole}$=173.1 GeV:

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

but vacuum metastable below!

metastability OK: unstable vacuum

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

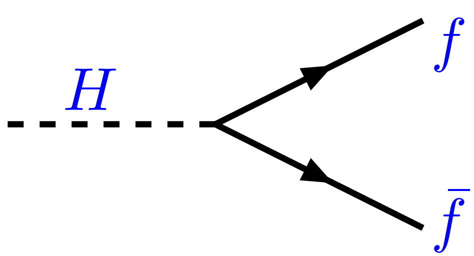


4. Higgs decays

Higgs couplings proportional to particle masses: once $\mathrm{M_H}$ 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:



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

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

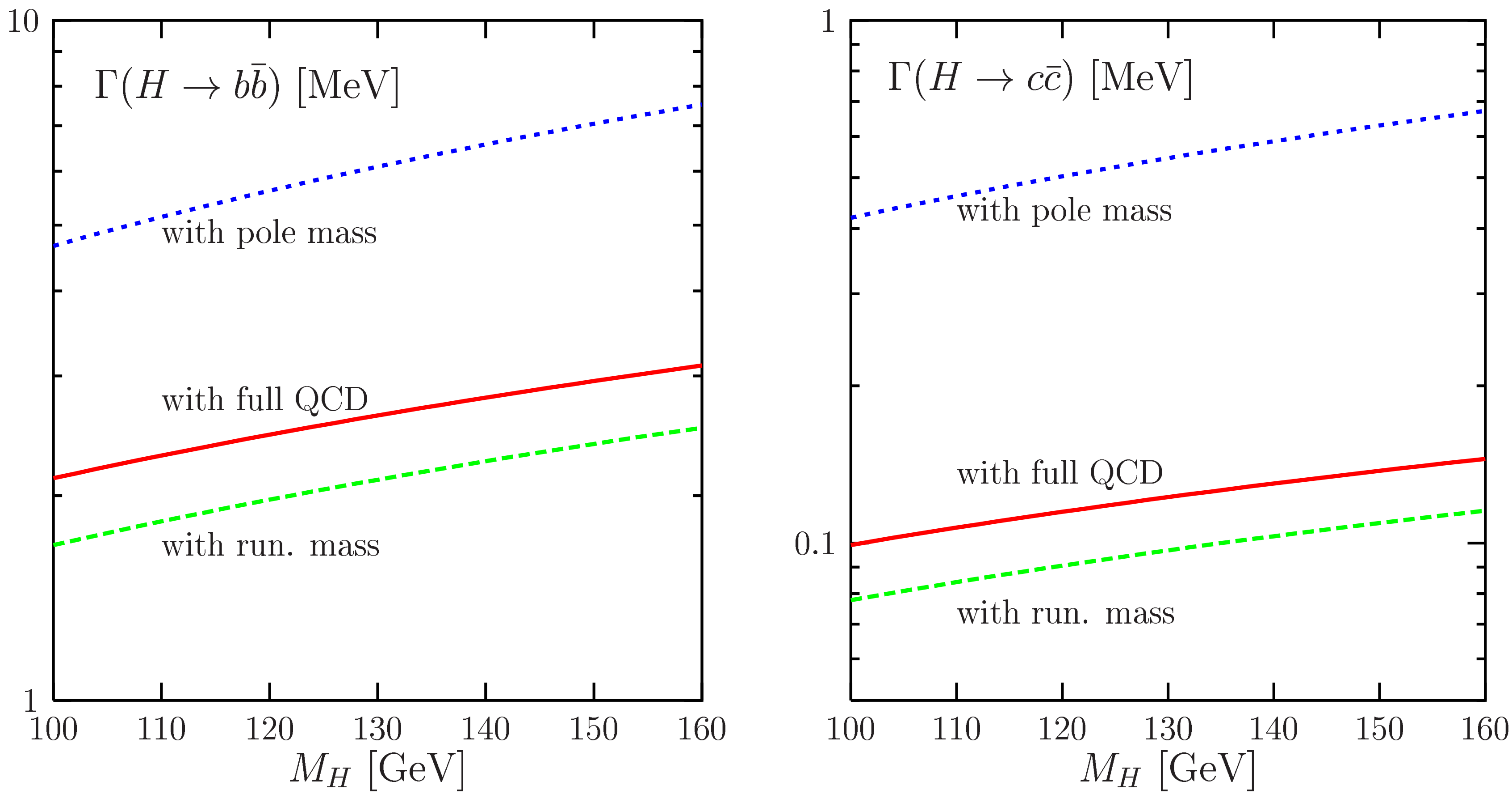
$$\mathrm{N_c = color\ number}$$

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

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

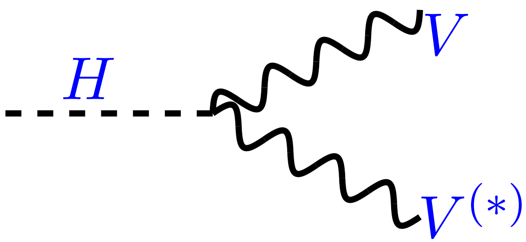
- **Include also direct QCD corrections (3 loops) and EW (one-loop).**

4. Higgs decays: QCD corrections



Partial widths for the decays $\mathrm{H} \to \mathrm{b\bar{b}}$ and $\mathrm{H} \to \mathrm{c\bar{c}}$ 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

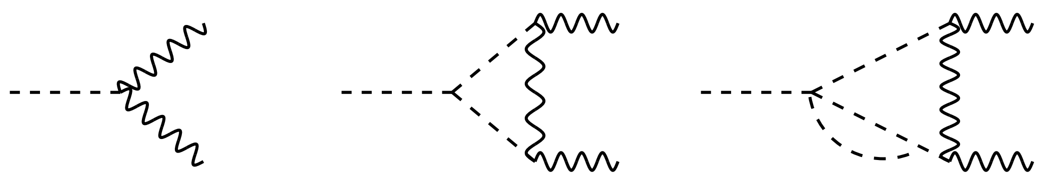
Electroweak radiative corrections to $\mathbf{H \to VV}$:

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

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

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

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



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

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

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

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

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

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

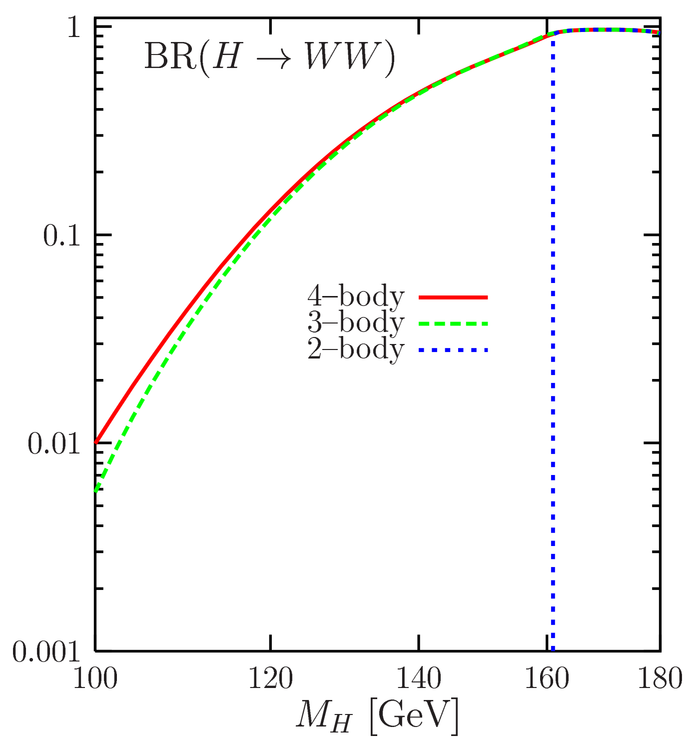
4. Higgs decays: decays into gauge bosons

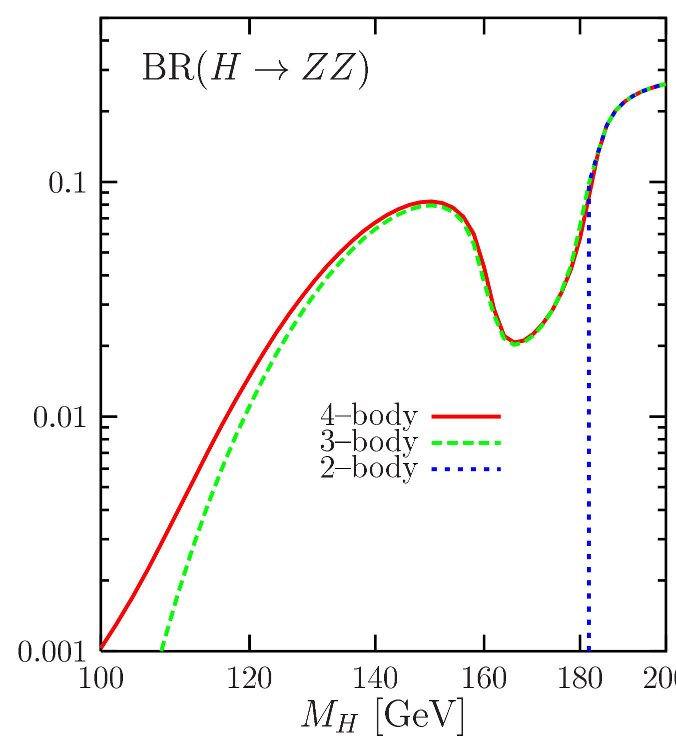
gd 2+3+4 body decay calculation of $\mathrm{H}\rightarrow\mathrm{V^*V^*}$:

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

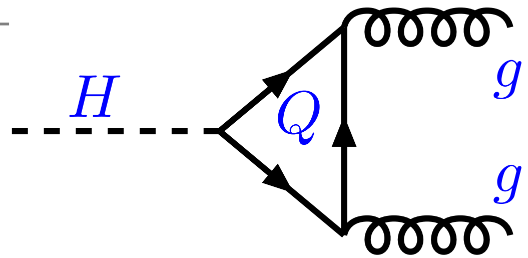
$\mathbf{\lambda(x,y;z)=(1-x/z-y/z)^2-4xy/z^2}$ **with** $\mathbf{\delta_{W/Z}=2/1}$ **and**

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





4. Higgs decays: decays into gluons



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

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

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

- 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.

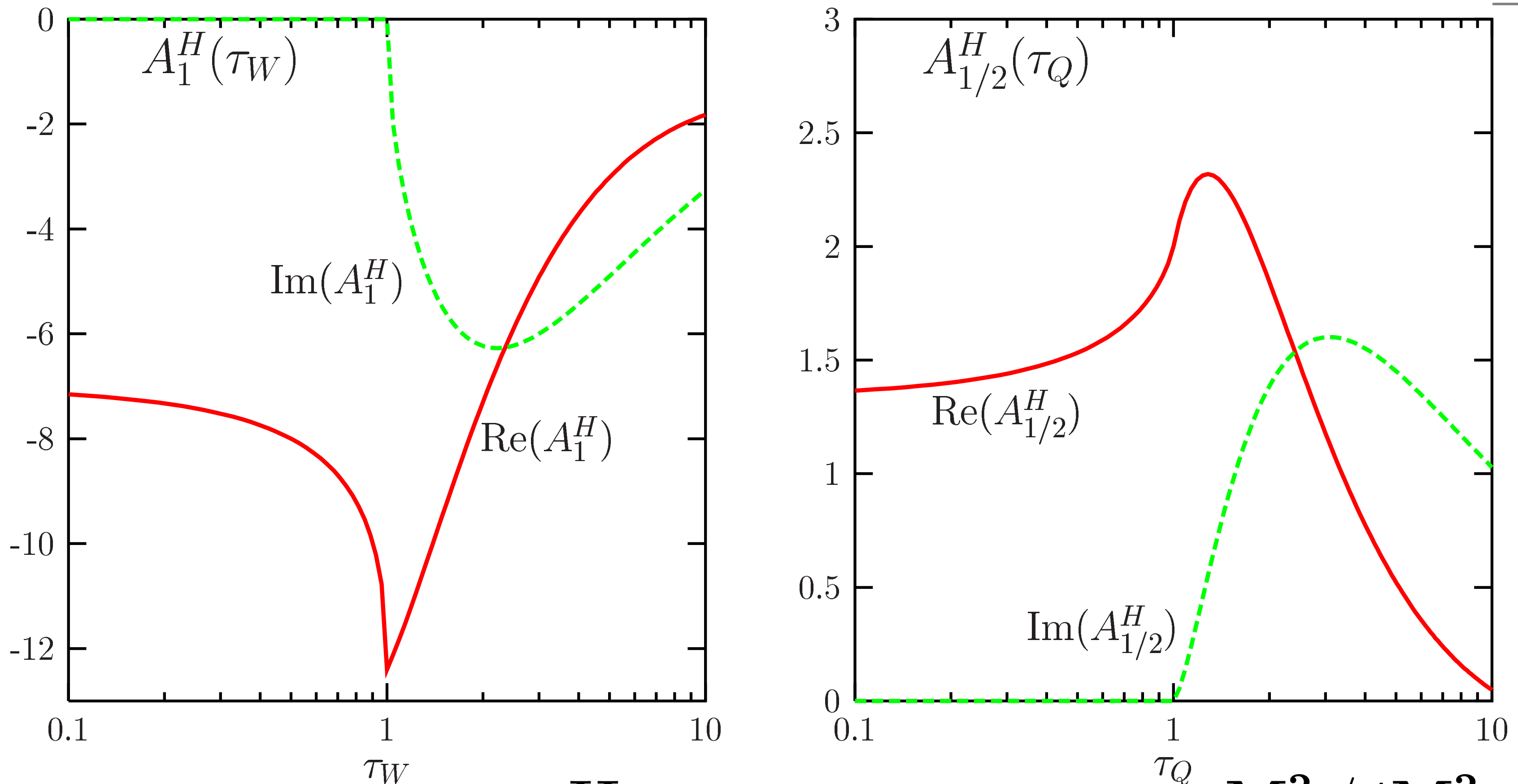
Good approximation in decay: include only t–loop with $m_Q \to \infty$. But:

- 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

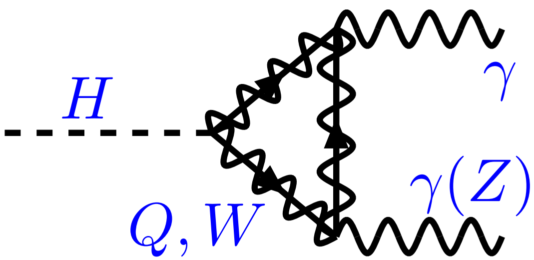


W and fermion amplitudes in $\mathrm{H}\to\gamma\gamma$ as function of $\tau_\mathbf{i} = \mathrm{M}_\mathbf{H}^2/4\mathrm{M}_\mathbf{i}^2$.

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

Trick for an easy calculation: low energy theorem for $\mathrm{M}_\mathbf{H} \ll \mathrm{Mi}$....

4. Higgs decays: decays into photons



$$\Gamma = \frac{G_\mu \alpha^2 M_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c e_f^2 A^H_{\frac{1}{2}}(\tau_f) + A^H_1(\tau_W) \right|^2$$

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

$$A^H_1(\tau) = -[2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)]\,\tau^{-2}$$

- 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!).

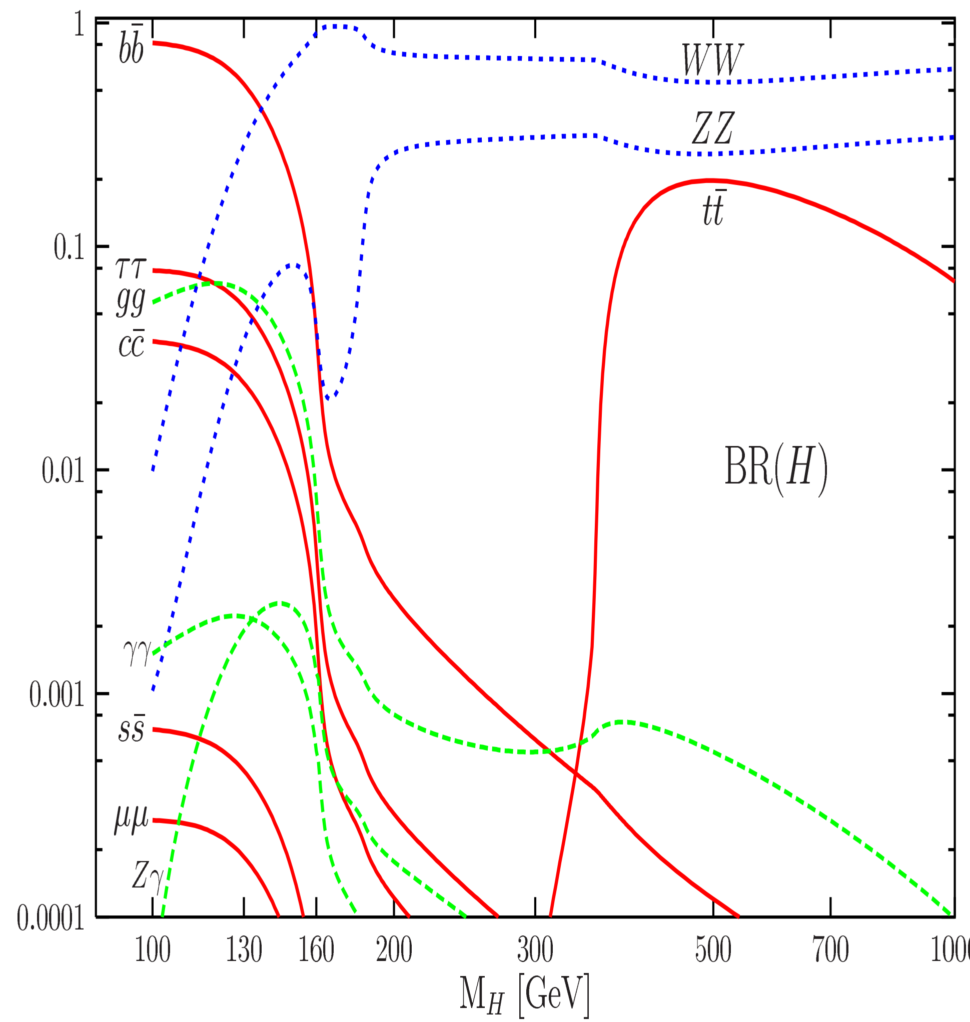
$\gamma\gamma$ width counts the number of charged particles coupling to Higgs!

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

- **'Low mass range', $\mathrm{M_H} \lesssim 130$ 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', $\mathrm{M_H} \gtrsim 130$ GeV:**
- – $\mathrm{H \to WW^*, ZZ^*}$ up to $\gtrsim 2\mathrm{M_W}$
- – $\mathrm{H \to WW, ZZ}$ above (BR $\to \frac{2}{3}, \frac{1}{3}$)
- – $\mathrm{H \to t\bar{t}}$ for high $\mathrm{M_H}$; BR $\lesssim 20\%$.
- **Total Higgs decay width:**
- – $\mathcal{O}$(MeV) for $\mathrm{M_H} \sim 100$ GeV (small)
- – $\mathcal{O}$(TeV) for $\mathrm{M_H} \sim 1$ TeV (obese).



4. Higgs decays: total width

Total decay width: $\Gamma_{\rm H} \equiv \sum_{\rm X} \Gamma(\rm H \to X)$

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

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

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

– $\rm H \to \gamma\gamma, \gamma Z$, **BR = a few permille.**

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

– $\rm H \to WW^*, ZZ^*$ **up to** $\gtrsim 2\rm M_W$

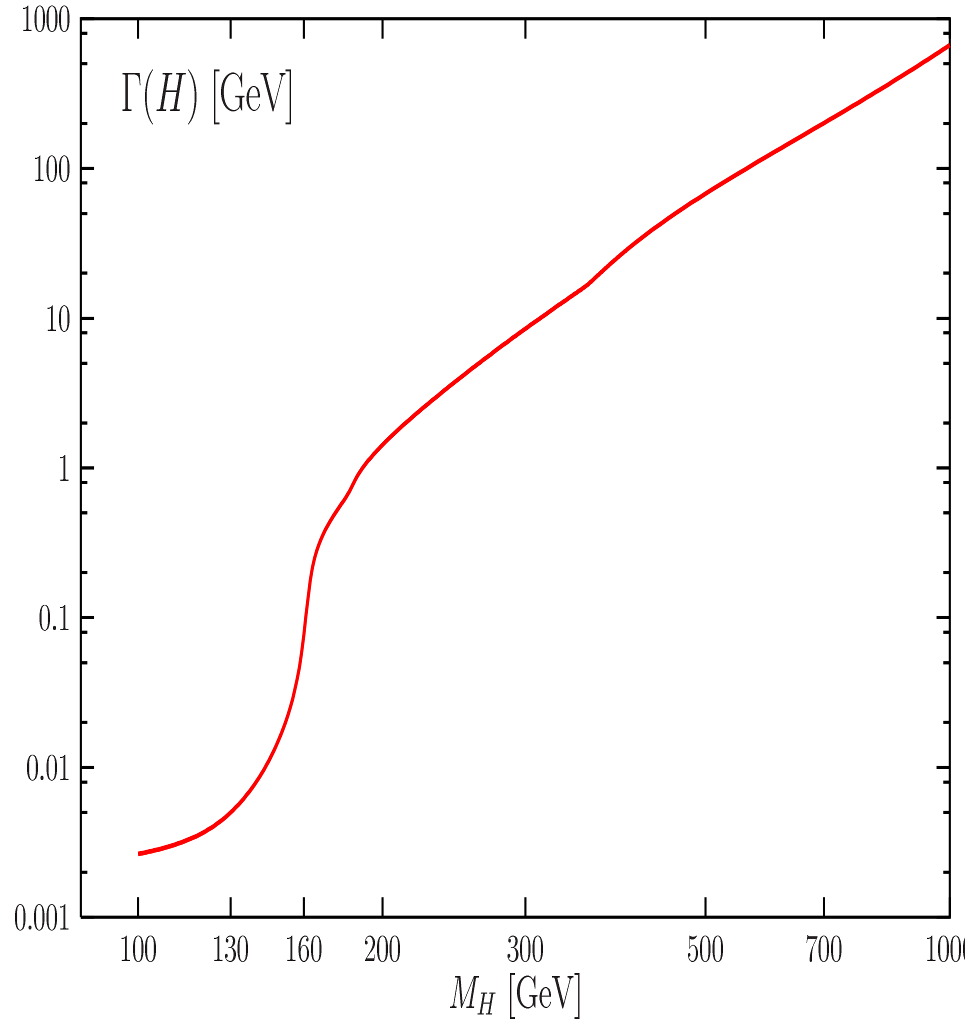
– $\rm H \to WW, ZZ$ **above (BR** $\to \frac{2}{3}, \frac{1}{3}$**)**

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

- **Total Higgs decay width:**

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

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



4. Higgs decays: theory uncertainties

However: there are theoretical uncertainties....

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

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

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

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

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

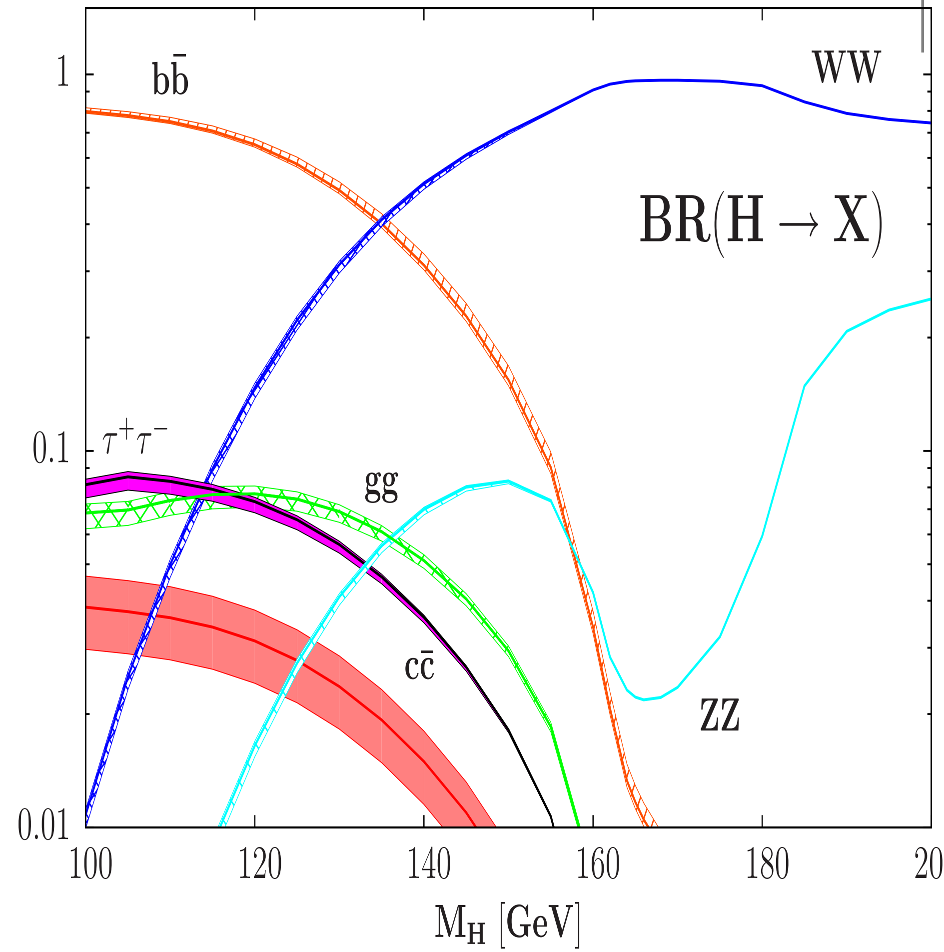
$\alpha_s(M_Z^2) = 0.1171 \pm 0.0014$ **@NNLO**

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

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

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

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

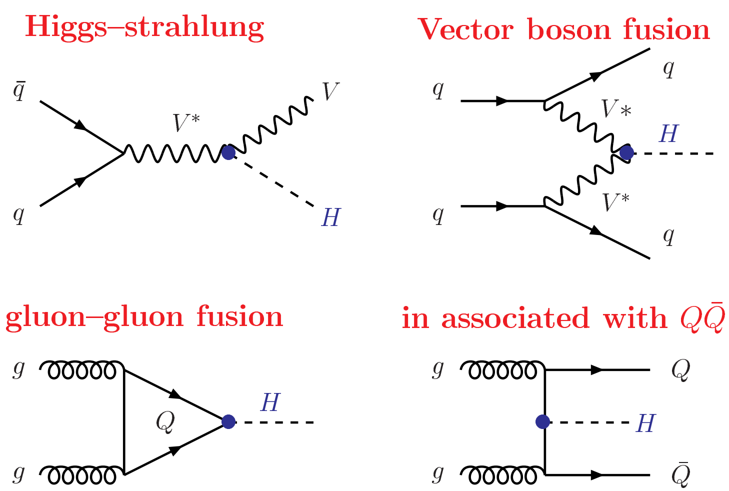


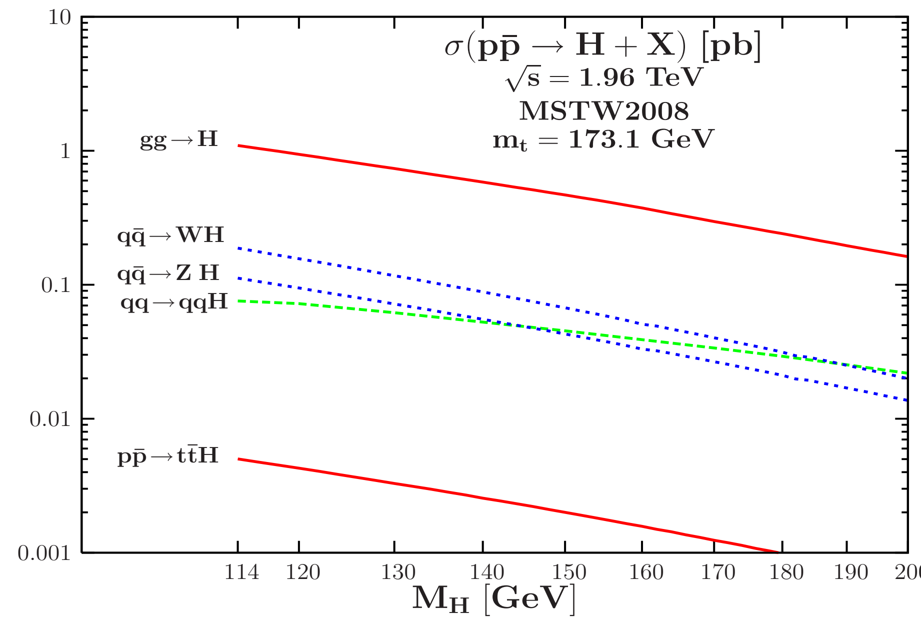
Include all items ⇒ non-negligible uncertainties.

esp. for M_H **≈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

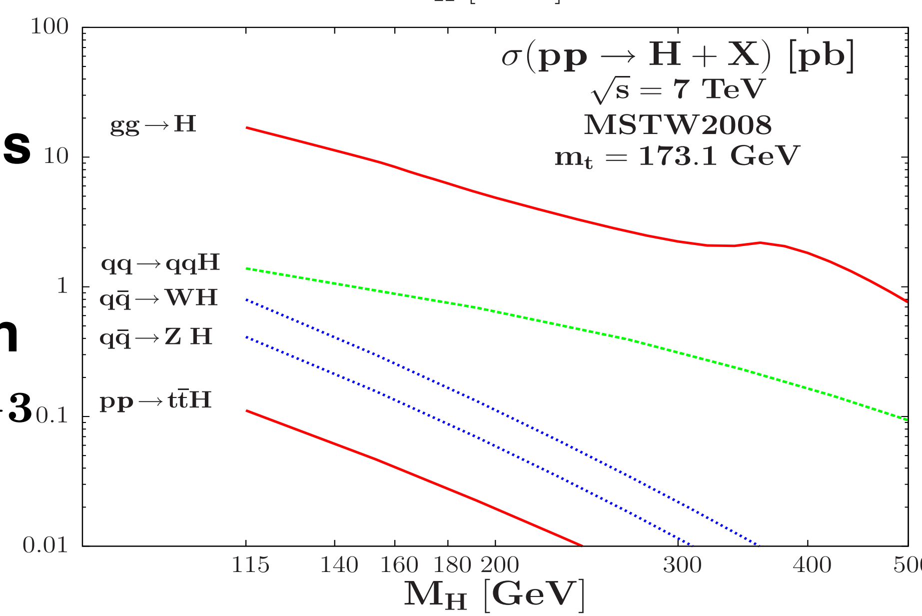
with gg→ H by far dominant process

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

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

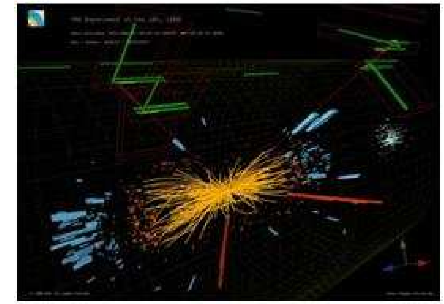
but eg BR(H$\to \gamma\gamma, ZZ \to 4\ell) \approx 10^{-3}$

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



5. SM Higgs at hadron colliders: generalities

$\Rightarrow$ **an extremely challenging task!**



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

  S/B $\gtrsim 10^{10} \Rightarrow$ a needle in a haystack!

- **Need some strong selection criteria:**

– trigger: get rid of uninteresting events...

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

– use specific kinematic features of Higgs

- **Combine # decay/production channels**

(and eventually several experiments...)

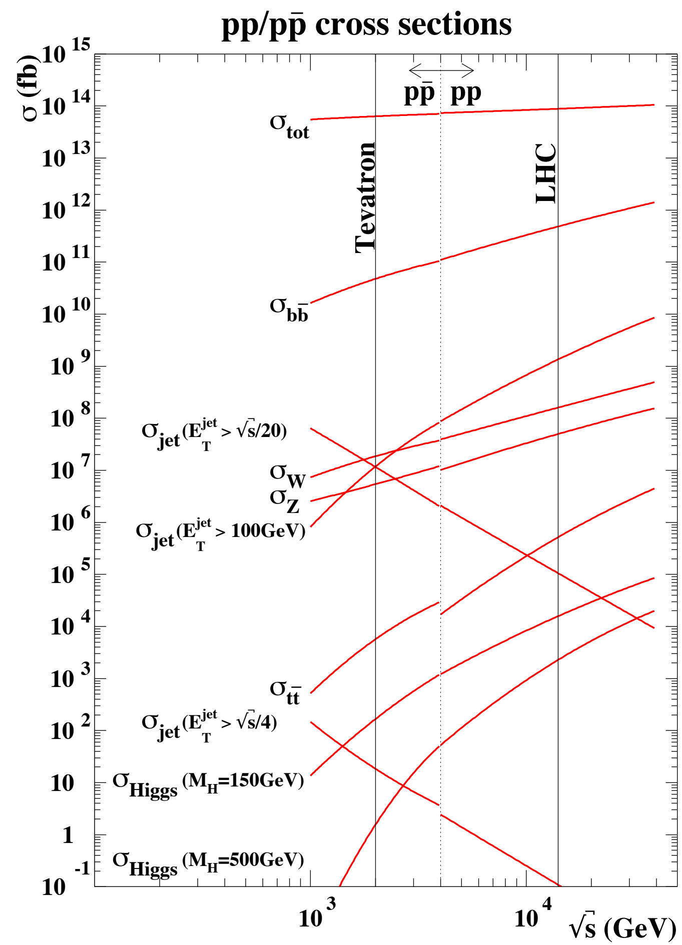
- **Have a precise knowledge of S and B rates**

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

- **Gigantic experimental + theoretical efforts**

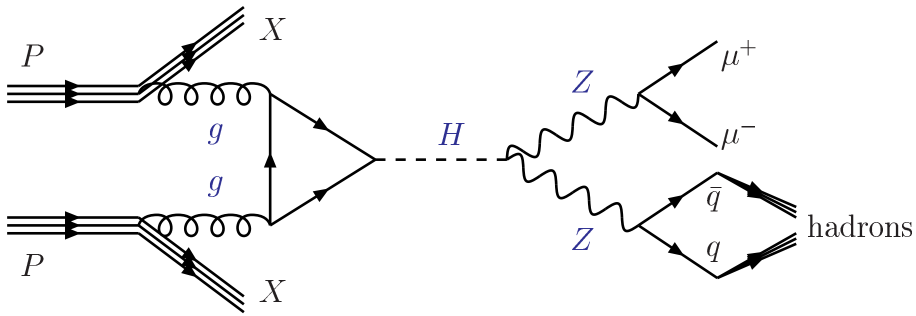
(more than 30 years of very hard work!)

For a flavor of how it is complicated from the theory side: a look at the $\mathrm{gg} \to \mathrm{H}$ 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 $\alpha_s^n \log^m(Q/M_H)$ 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. $p_T, \eta, \frac{d\sigma}{dM}$) to distinguish S from B.

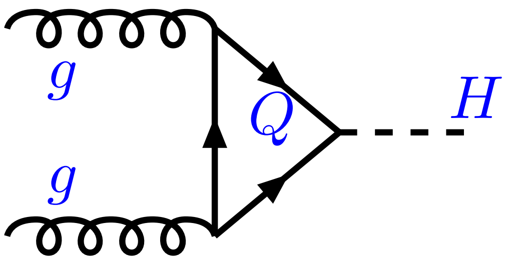
In fact, one has to do this for both the signal and background (unless directly measurable from data): the important quantity is $\sigma = \frac{N_S}{\sqrt{N_{bjg}}}$

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

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

5. SM Higgs production: gg fusion

Let us look at this main Higgs production channel at the LHC in detail.



$$\hat{\sigma}_{\rm LO}(\mathbf{gg \to H}) = \frac{\pi^2}{8\mathbf{M_H}}\Gamma_{\rm LO}(\mathbf{H \to gg})\delta(\hat{\mathbf{s}} - \mathbf{M_H^2})$$

$$\sigma_0^{\mathbf{H}} = \frac{\mathbf{G}_\mu \alpha_s^2(\mu_R^2)}{288\sqrt{2}\pi} \left| \frac{3}{4} \sum_q \mathbf{A}^{\mathbf{H}}_{1/2}(\tau_Q) \right|^2$$

Related to the Higgs decay width into gluons discussed previously.

- **In SM: only top quark loop relevant, b–loop contribution $\lesssim 5\%$.**
- **For $m_Q \to \infty, \tau_Q \sim 0 \Rightarrow A_{1/2} = \frac{4}{3} =$ constant and $\hat{\sigma}$ finite.**
- **Approximation $m_Q \to \infty$ valid for $M_H \lesssim 2m_t = 350$ GeV.**

Gluon luminosities large at high energy+strong QCD and Htt couplings

$gg \to H$ is the leading production process at the LHC.

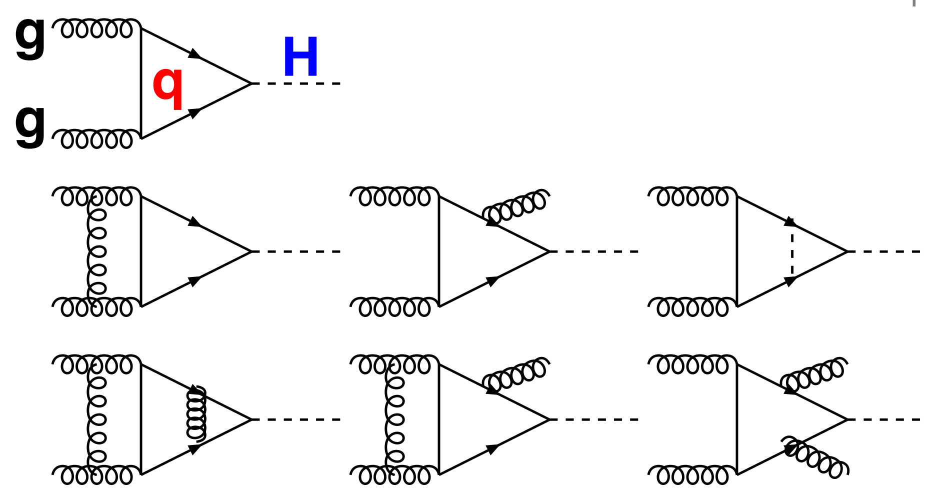
- **Very large QCD RC: the two– and three–loops have to be included.**
- **Also the Higgs P_T is zero at LO, must generated at NLO.**

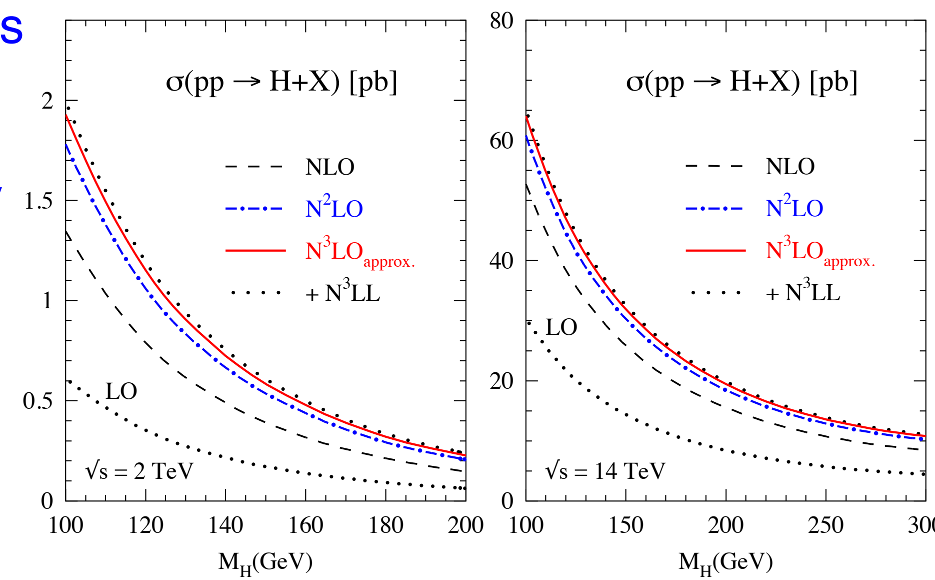
5. SM Higgs production: gg fusion

LO[a]: already at one loop
QCD: exact NLO[b] : $\mathrm{K} \approx 2$ (1.7)
EFT NLO[c]: good approx.
EFT NNLO[d]: $\mathrm{K} \approx 3$ (2)
EFT NNLL[e]: $\approx +10\%$ (5%)
EFT other HO[f]: a few %.
EW: EFT NLO: [g]: $\approx \pm$ very small
exact NLO[h]: $\approx \pm$ a few %
QCD+EW[i]: a few %
Distributions: two programs[j]

[a] Georgi+Glashow+Machacek+Nanopoulos
[b] Spira+Graudenz+Zerwas+AD (exact)
[c] Spira+Zerwas+AD; Dawson (EFT)
[d] Harlander+Kilgore, Anastasiou+Melnikov Ravindran+Smith+van Neerven
[e] Catani+de Florian+Grazzini+Nason
[f] Moch+Vogt; Ahrens et al.
[g] Gambino+AD; Degrassi et al.
[h] Actis+Passarino+Sturm+Uccirati
[i] Anastasiou+Boughezal+Pietriello
[j] Anastasiou et al.; Grazzini

The $\sigma^{\mathrm{theory}}_{gg\to H}$ long story (70s–now) ...





Moch+Vogt

5. SM Higgs production: gg fusion

- **At NLO: corrections known exactly, i.e. for finite $\mathrm{m_t}$ and $\mathrm{M_H}$:**

– quark mass effects are important for $\mathrm{M_H} \gtrsim 2\mathrm{m_t}$.

– $\mathrm{m_t} \to \infty$ is still a good approximation for masses below 300 GeV.

– corrections are large, increase cross section by a factor 2 to 3.

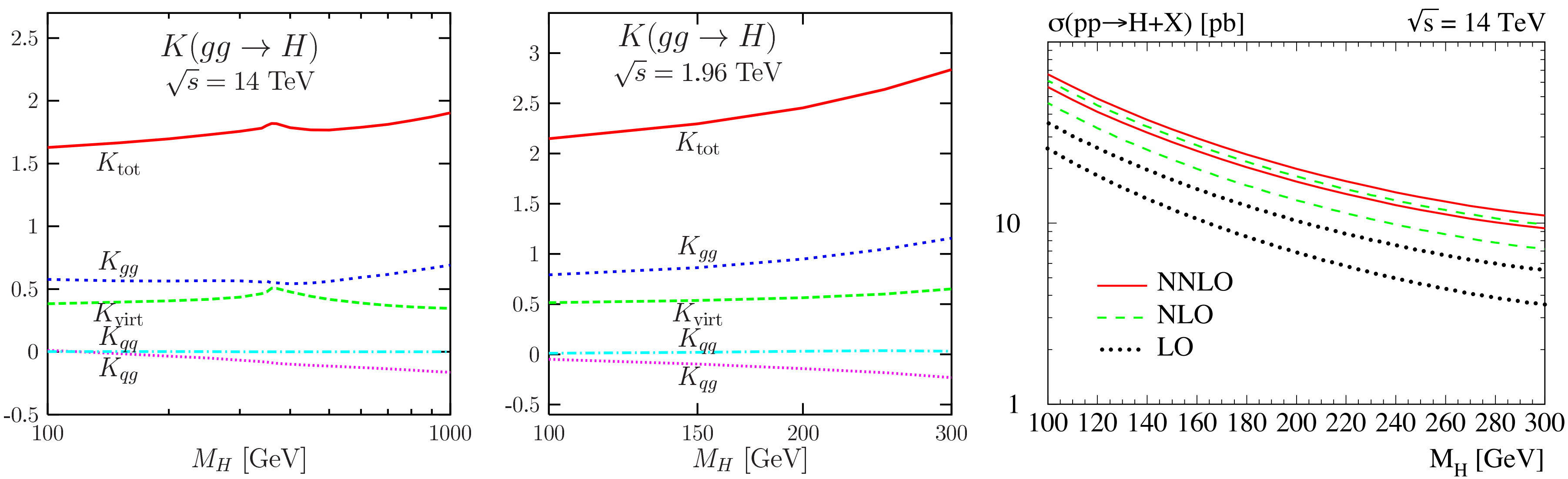
- **Corrections have been calculated in $\mathrm{m_t} \to \infty$ limit beyond NLO.**

– moderate increase at NNLO by 30% and stabilisation with scales...

– soft–gluon resummation performed up to NNLL: $\approx$ 5–10% effects.

Note 1: NLO corrections to P_T, η distributions are also known.

Note 2: NLO EW corrections are also available, they are rather small.



5. SM Higgs production: gg fusion

Despite of that, the $gg \to H$ cross section still affected by uncertainties

- **Higher-order or scale uncertainties:**

K-factors large $\Rightarrow$ HO could be important
HO estimated by varying scales of process

$$\mu_0/\kappa \leq \mu_R, \mu_F \leq \kappa\mu_0$$

at lHC: $\mu_0 = \frac{1}{2}M_H, \kappa = 2 \Rightarrow \Delta_{scale} \approx 10\%$

- **gluon PDF+associated α_s uncertainties:**

gluon PDF at high–x less constrained by data
α_s uncertainty (WA, DIS?) affects $\sigma \propto \alpha_s^2$
$\Rightarrow$ large discrepancy between NNLO PDFs
PDF4LHC recommend: $\Delta_{pdf} \approx 10\%$@lHC

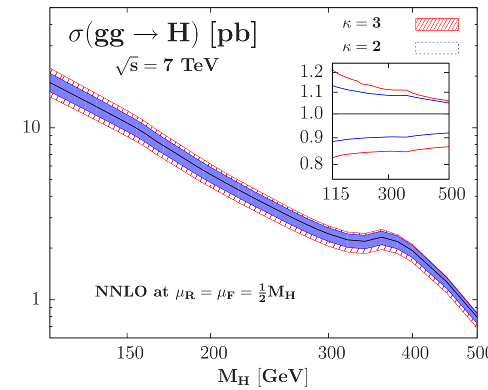
- **Uncertainty from EFT approach at NNLO**

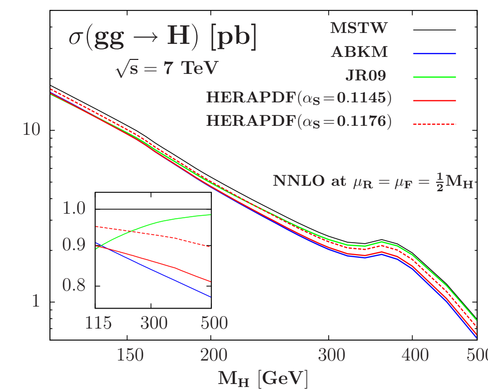
$m_{loop} \gg M_H$ good for top if $M_H \lesssim 2m_t$
but not above and not b ($\approx 10\%$), W/Z loops
Estimate from (exact) NLO: $\Delta_{EFT} \approx 5\%$

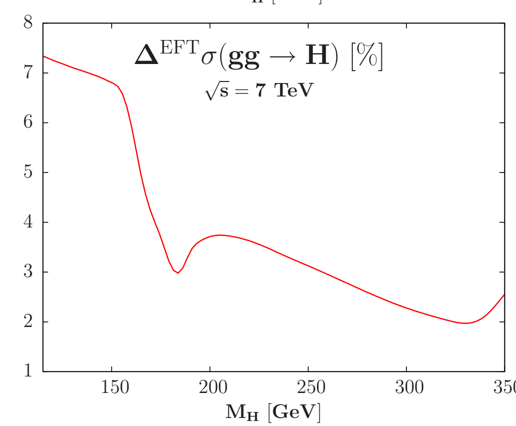
- **Include ΔBR(H$\to$X) of at most few %**

total $\Delta\sigma^{NNLO}_{gg\to H\to X} \approx$ 20–25%@lHC

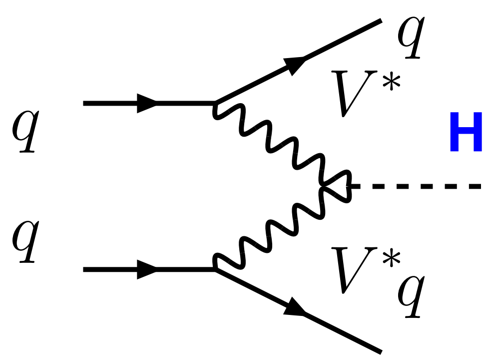
LHC-HxsWG; Baglio+AD $\Rightarrow$







5. SM Higgs production: WW fusion



$$\hat{\sigma}_{\rm LO} = \frac{\mathbf{16\pi^2}}{\mathbf{M_H^3}} \Gamma(\mathbf{H \to V_L V_L}) \frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\tau}\Big|_{\mathbf{V_L V_L/qq}}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\tau}\Big|_{\mathbf{V_L V_L/qq}} \sim \frac{\alpha}{\mathbf{4\pi^3}} (\mathbf{v_q^2} + \mathbf{a_q^2})^{\mathbf{2}} \log\left(\frac{\hat{\mathbf{s}}}{\mathbf{M_H^2}}\right)$$

Three–body final state: analytical expression rather complicated...

Simple form in LVBA: σ related to $\Gamma(\mathrm{H} \to \mathbf{VV})$ and $\frac{\mathbf{d}\mathcal{L}}{\mathbf{d}\tau}\big|_{\mathbf{V_L V_L/qq}}$

Not too bad approximation at $\sqrt{\hat{\mathrm{s}}} \gg \mathrm{M_H}$: a factor 2 accurate.

Large cross section: in particular for small $\mathrm{M_H}$ and large c.m. energy:

$\Rightarrow$ most important process at the LHC after $\mathrm{gg} \to \mathrm{H}$.

QCD radiative corrections small: order 10% (also for distributions).

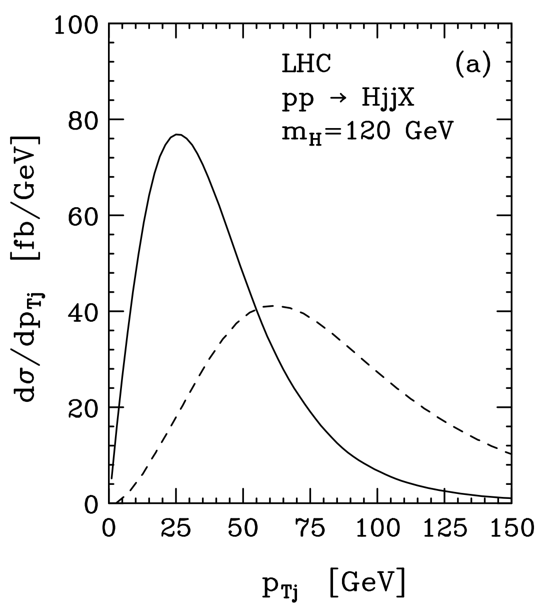
In fact: at LO in/out quarks are in color singlets and at NLO: no gluons are exchanged between first/second incoming (outgoing) quarks: QCD corrections only consist of known corrections to the PDFs!

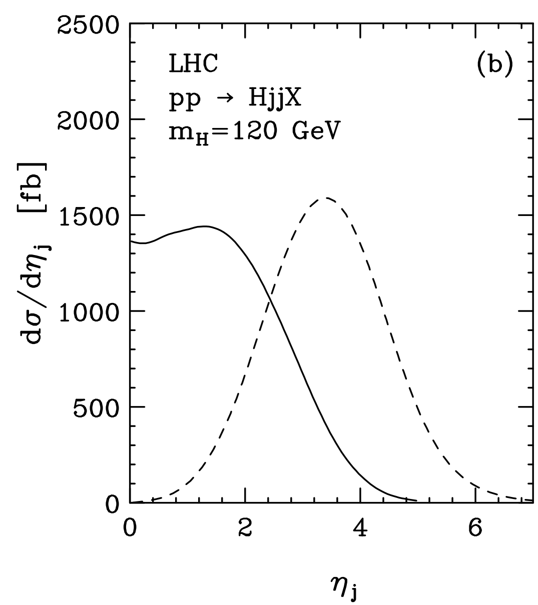
5. SM Higgs production: WW fusion

Kinematics of the process: a very specific kinematics indeed....

- Forward jet tagging: the two final jets are very forward peaked.
- They have large energies of $\mathcal{O}$(1 TeV) and sizeable $\mathrm{P_T}$ of $\mathcal{O}(\mathrm{M_V})$.
- Central jet vetoing: Higgs decay products are central and isotropic.
- Small hadronic activity in the central region no QCD (trigger uppon).

Allow to suppress the background to the level of H signal: $\mathrm{S/B} \sim 1$.

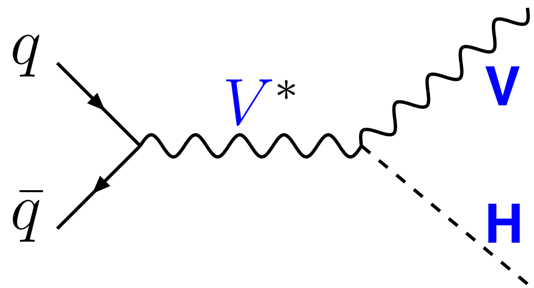




——— lowest/central jet   - - - - highest/central jet

5. SM Higgs production: associated HV

The associated HV production:



$$\hat{\sigma}_{\rm LO}(\mathbf{q\bar{q}} \to \mathbf{VH}) = \frac{\mathbf{G}_\mu^2 \mathbf{M}_\mathbf{V}^4}{\mathbf{288}\pi \hat{\mathbf{s}}} \times (\hat{\mathbf{v}}_\mathbf{q}^2 + \hat{\mathbf{a}}_\mathbf{q}^2) \lambda^{1/2} \frac{\lambda + \mathbf{12M_V^2}/\hat{\mathbf{s}}}{(\mathbf{1} - \mathbf{M_V^2}/\hat{\mathbf{s}})^2}$$

Similar to $\mathrm{e^+e^- \to HZ}$ process used for Higgs searches at LEP2.

Cross section $\propto \hat{\mathrm{s}}^{-1}$ sizable only for low $\mathrm{M_H} \lesssim 200$ GeV values.

Cross section for $\mathrm{W^\pm H}$ approximately 2 times larger than ZH.

In fact, simply Drell–Yan production of virtual boson with $\mathrm{q}^2 \neq \mathrm{M}_\mathrm{V}^2$

$$\hat{\sigma}(\mathbf{q\bar{q}} \to \mathbf{HV}) = \hat{\sigma}(\mathbf{q\bar{q}} \to \mathbf{V}^*) \times \frac{\mathbf{d\Gamma}}{\mathbf{dq^2}}(\mathbf{V}^* \to \mathbf{HV})$$

$\Rightarrow$ radiative corrections are mainly those of the known DY process

(at 2-loop, need to consider also $\mathrm{gg \to HZ}$ through box which is $\neq$).

5. SM Higgs production: associated HV

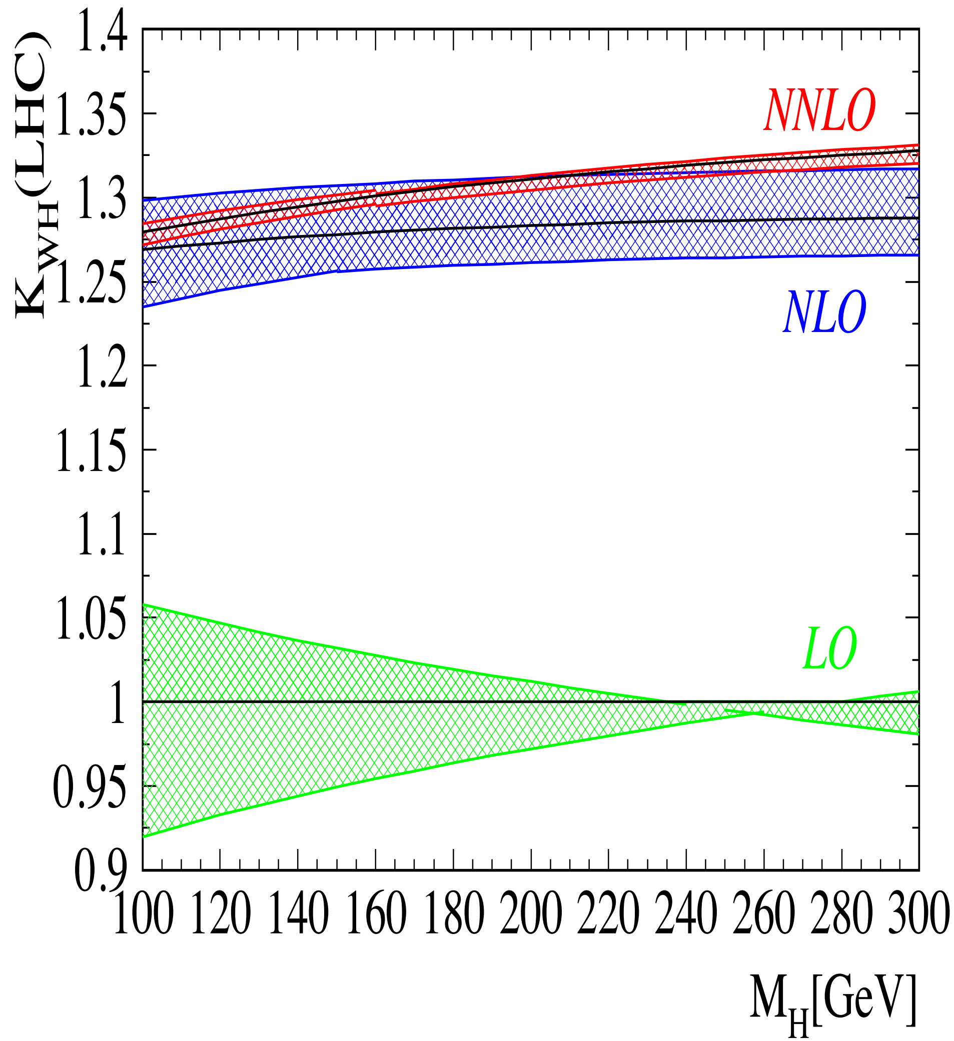
Radiative corrections needed:
– for precise determination of σ
– stability against scale variation

HO also needed to fix scales:
– renormalization μ_R for α_s
– factorization μ_F for matching.

RC parameterized by K–factor:

$$K = \frac{\sigma_{HO}(pp \to H+X)}{\sigma_{LO}(pp \to H+X)}$$

Can also define K-factor at LO.
QCD RC in HV known up to NNLO
(borrowed from Drell-Yan: K$\approx$ 1.4)
EW RC known at $\mathcal{O}(\alpha)$: small.

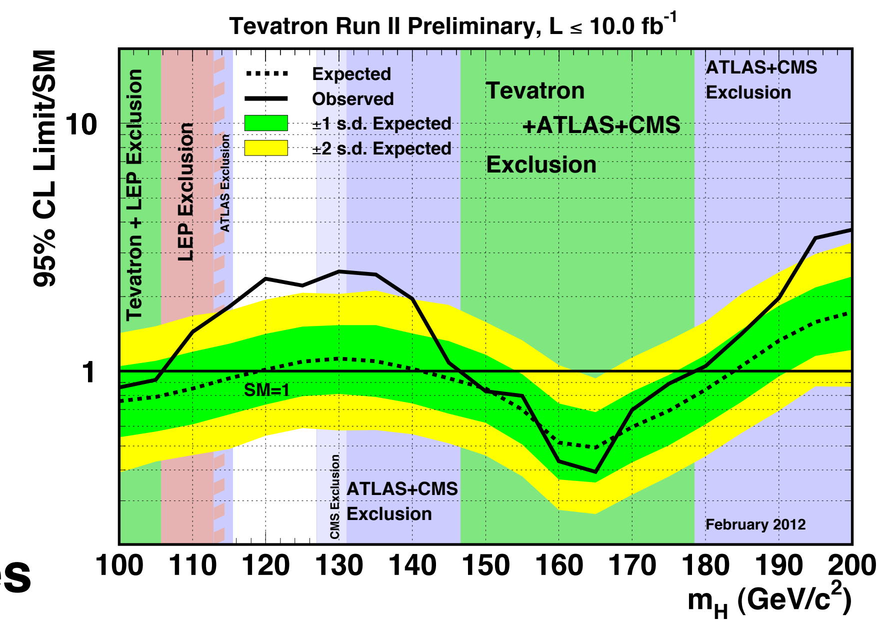


Radiative corrections to various distributions are also known.
Process fully implemented in various MC programs used by experiments

5. SM Higgs production: associated HV

Up-to-now, it only plays a marginal role at the LHC (small rates etc...).
Interesting final states are: $\mathrm{WH} \to \gamma\gamma\ell, \mathrm{b\bar{b}}\ell, 3\ell$ **and** $\mathrm{ZH} \to \mathrm{q\bar{q}}\nu\nu$.
$\mathrm{ZH} \to \ell\ell\mathrm{b\bar{b}}$ **at high** $\mathrm{P_T}$**: jet substructure (**$\mathrm{H} \to \mathrm{b\bar{b}} \neq \mathrm{g}^* \to \mathrm{q\bar{q}}$.
Analyses by ATLAS+CMS: 5σ **disc. possible at 14 TeV with** $\mathcal{L} \gtrsim 100$ **fb.**
But very clean channel when normalized to $\mathrm{pp} \to \mathrm{Z}$**: measurements!**

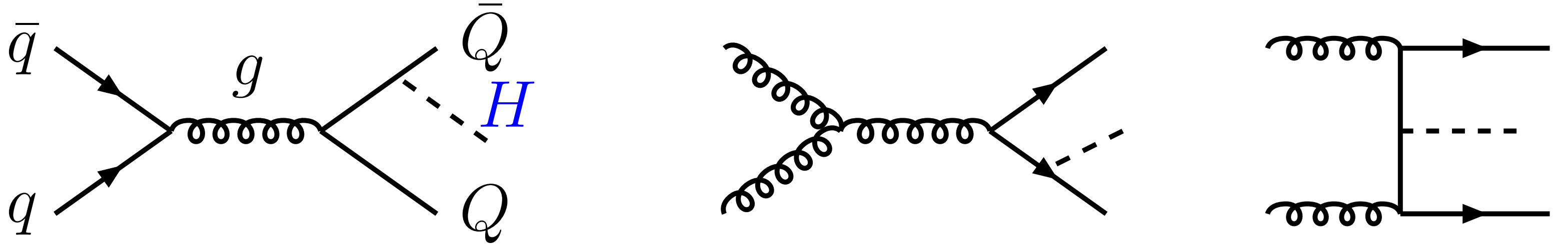
However: WH channel is the most important at Tevatron:
$\mathrm{M_H} \lesssim 130$ **GeV:** $\mathrm{H} \to \mathrm{b\bar{b}}$
$\Rightarrow \ell\nu\mathrm{b\bar{b}},\ \nu\bar{\nu}\mathrm{b\bar{b}},\ \ell^+\ell^-\mathrm{b\bar{b}}$
(help for $\mathrm{HZ} \to \mathrm{b\bar{b}}\ell\ell, \mathrm{b\bar{b}}\nu\nu)$
$\mathrm{M_H} \gtrsim 130$ **GeV:** $\mathrm{H} \to \mathrm{WW}^*$
$\Rightarrow\ \ell^{\pm}\ell^{\pm}\mathrm{jj},\ 3\ell^{\pm}$



Sensitivity in the low H mass range: excludes low $\mathrm{M_H} \lesssim 110$ **GeV values**
≈3σ **excess for** $\mathrm{M_H}$ **=115–135 GeV!**

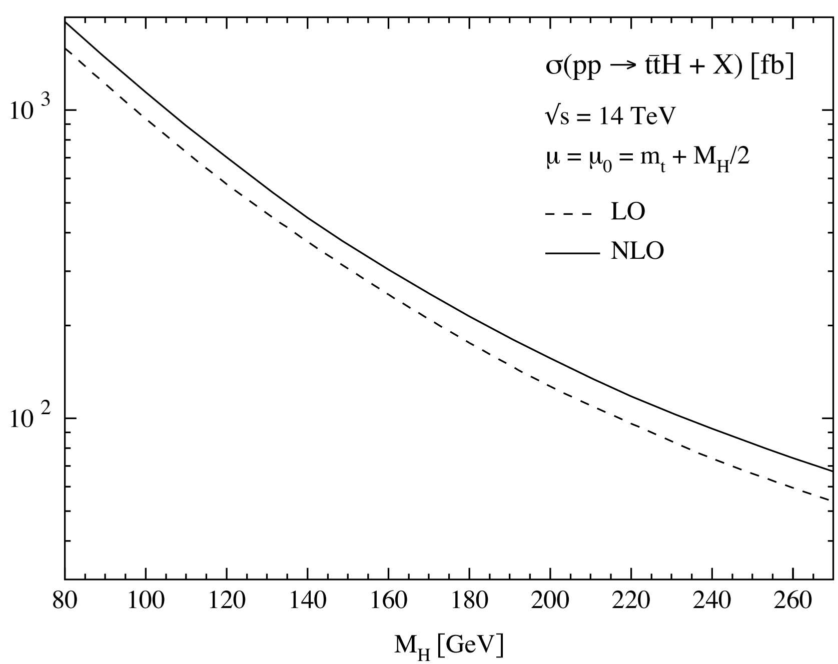
5. SM Higgs production: Htt production

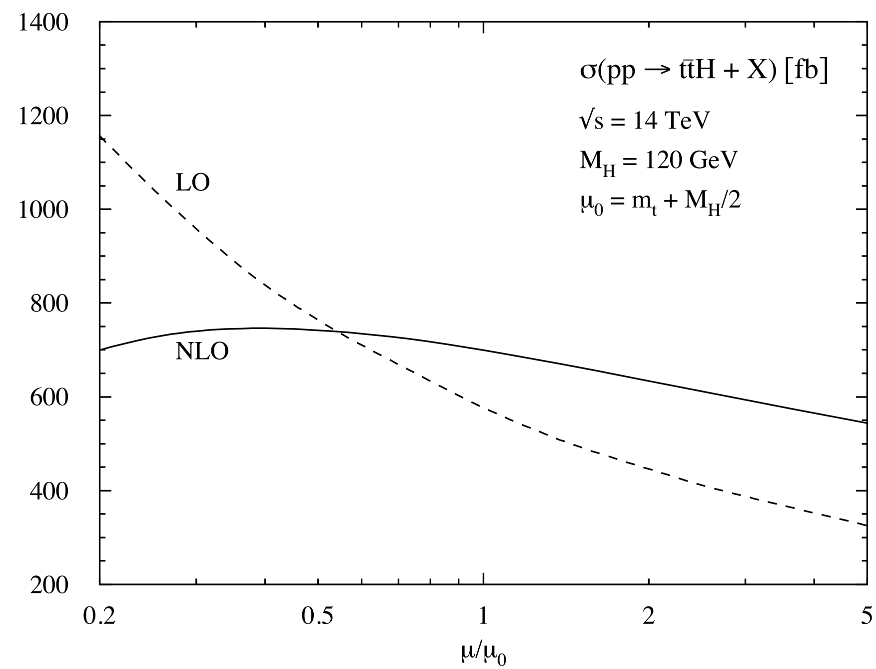
Most complicated process for Higgs production in pp: many channels:



NLO QCD corrections also calculated:

small K–factors ($\approx$ 1–1.2) but strong reduction of scale variation!





5. SM Higgs production: Htt production

Small corrections to kinematical distributions (e.g: p_T^{top}, P_T^H), etc...

- Rather tiny uncertainties from higher orders, PDFs.
- Other possible processes involving heavy quarks work only in BSM:

– Single top+Higgs production: $pp \to tH + X$.

– Associated production with bottom quarks: $pp \to bbH$.

Interesting signals at the LHC for this process are:

- $pp \to Htt \to \gamma\gamma\ell^{\pm}$: clean but rather small rates.
- $pp \to Htt \to b\bar{b}\ell^{\pm}$: needs efficent b tagging; large jet bkg!
- $pp \to Htt \to \ell^{\mp}\ell^{\pm}\nu\nu$: large bckgs from ttWjj, etc...

Possibility for a 3–5 signal at $M_H \lesssim 140$ GeV with high luminosity.

Needs to be combined with similar channels and topologies (eg:

$pp \to WH \to \ell\gamma\gamma, \ell b\bar{b}$ to increase total signal significance.

But process very important for measurement of Htt Yukawa coupling!

5. SM Higgs production: expectations

(better look at G. Tonelli slides...)

At lHC: $\sqrt{s}=7$ TeV and $\mathcal{L}\approx \mathrm{few\ fb}^{-1}$

5σ discovery for $M_H \approx$130–200 GeV

95%CL sensitivity for $M_H \lesssim$600 GeV

$gg\to H\to\gamma\gamma$ ($M_H \lesssim$ 130 GeV)

$gg\to H\to ZZ\to 4\ell, 2\ell 2\nu, 2\ell 2b$

$gg\to H\to WW\to \ell\nu\ell\nu + 0, 1$ jets

Even better at 8 TeV and higher $\mathcal{L}$!

help from VBF/VH and $gg\to H\to\tau\tau$

Tevatron had still some data to analyze

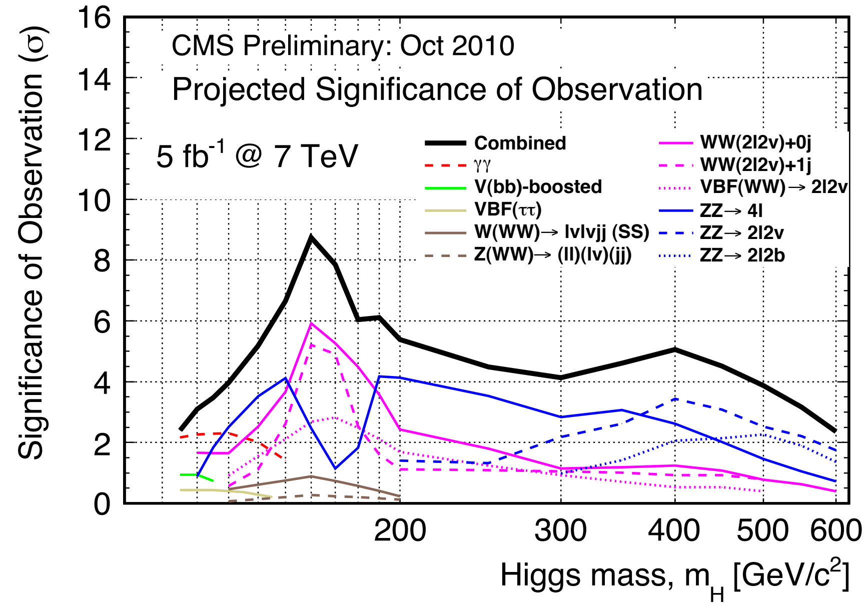
$HV \to b\bar{b}\ell X @ M_H \lesssim$130 GeV!!

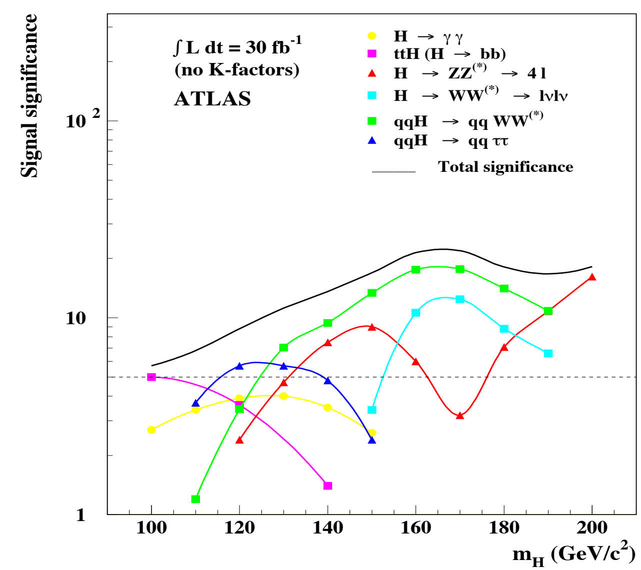
Full LHC: same as lHC plus some others

– VBF: $qqH \to \tau\tau, \gamma\gamma, ZZ^*, WW^*$

– VH$\to$Vbb with jet substructure tech.

– ttH: H$\to\gamma\gamma$ bonus, H$\to b\bar{b}$ hopeless?





Conclusion? Mission accomplie!