Particle Physics $\equiv$ EWSB after LHC 8

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I: The SM and EWSB

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

II: Higgs Physics

- Higgs decays
- Higgs production a hadron colliders
- Implications of the discovery

III: Beyond the SM:

- Why beyond the SM?
- The case of SUSY and the MSSM
- What next?

1. The Standard Model: brief introduction

The Standard Model describes electromagnetic, strong and weak interactions:

Electromagnetic interaction (QED):

– subjects: electric charged particles,
– mediator: one massless photon,
– conserves P, C, T... et of course Q.

Strong (nuclear) interaction (QCD):

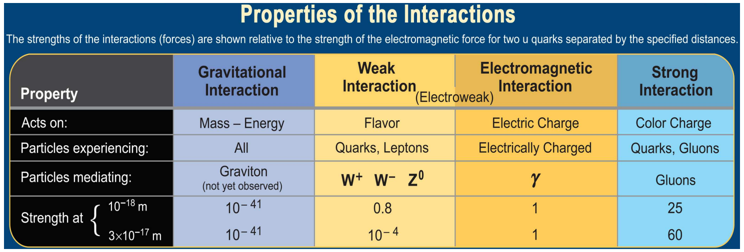
– quarks appearing in three q,q ,q,
– interacting via exchange of color,
– mediators: the massless gluons,
– conserves P,C,T and color number;
– color=attractive ⇒ confinement!

Weak (nuclear) interaction:

– subjects: all fermions;
– mediators: massive W^+, W^-, Z!
(only short range interaction),
– does not conserve parity: $f_L \neq f_R$;
(ex: no $\nu_R \Rightarrow \nu$ masseless);
– does not conserve CP: $n_P \gg n_{\bar{P}}$.

Particules de: matière (s=1/2) force (s=1)
3 familles de fermions bosons-jauge

 c→ Q→ m→	quark up ^{3}u +2/3 $\sim$5 MeV	quark charm ^{3}c +2/3 1.6 GeV	quark top ^{3}t +2/3 172 GeV	gluon ^{8}g 0 0
	quark down ^{3}d −1/3 $\sim$5 MeV	quark strange ^{3}s −1/3 0.2 GeV	quark bottom ^{3}b −1/3 4.9 GeV	photon γ 0 0
	neutrino e ν_e 0 ~ 0	neutrino μ ν_μ 0 ~ 0	τ neutrino ν_τ 0 ~ 0	boson Z Z^0 0 91.2 GeV
	electron e −1 0.5 MeV	muon μ −1 0.1 GeV	tau τ −1 1.7 GeV	bosons W $W^\pm$ ±1 80.4 GeV



Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at { 10^{-18} m	10^{-41}	0.8	1	25
Strength at { 3×10^{-17} m	10^{-41}	10^{-4}	1	60

1. The Standard Model: brief introduction

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

- relativistic quantum field theory: quantum mechanics+special relativity,
- based on gauge symmetry: invariance under internal symmetry group,
- a carbon–copy of QED, the quantum field theory of electromagnetism.

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

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

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

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, consistent, aesthetical and extremely successful theory:

- minimal coupling: interaction uniquely determined once group fixed,
- invariance implies massless photon and allows massive fermions,
- mathematically consistent: perturbative, unitary, renormalisable,
- very predictive theoretically and very well tested experimentally.

1. The Standard Model: brief introduction

SM is based on the gauge symmetry $\mathrm{G_{SM} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y}$

- The local/gauge symmetry group $\mathrm{SU(3)_C}$ describes the strong force:

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

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

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

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

$\Rightarrow$ the partons are free at high-energy and confined at low-energies...

The Lagrangian of the theory is a simple extension of the one of QED:

$$\mathcal{L}_\mathrm{QCD} = -\frac{1}{4}\mathrm{G^a_{\mu\nu} G^{\mu\nu}_a + i \sum_i \bar{q}_i D_\mu \gamma^\mu q_i} \;\; \mathrm{(-\sum_i m_i \bar{q}_i q_i)}$$

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

$$\mathrm{D_\mu = \partial_\mu - i g_s T_a G^a_\mu}.$$

Interactions/couplings are then uniquely determined by SU(3) structure:

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

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

– the gluons are massless while quarks can be massive (like in QED)...

1. The Standard Model: brief introduction

SM is based on the gauge symmetry $\mathbf{G_{SM} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y}$

- $\mathbf{SU(2)_L \times U(1)_Y}$ **describes the electromagnetic+weak=EW interaction:**

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

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

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

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

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

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

corresping to the 3 generators (Pauli matrices) of SU(2) and are massless

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

Lagrangian simple: with fields strengths and covariant derivatives as QED

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

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

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

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:

⇒ The Brout-Englert-Higgs mechanism ⇒ the Higgs particle H.

2. The Higgs mechanism 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 ⇒ spontaneous EW symmetry breaking:

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

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

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

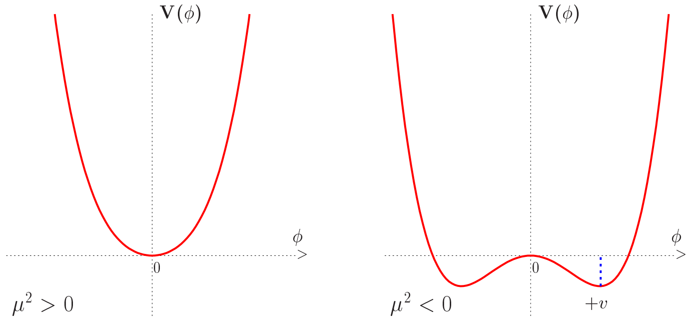
$\mu^2 > 0$: **4 scalar particles..**

$\mu^2 < 0$: Φ **develops a vev:**

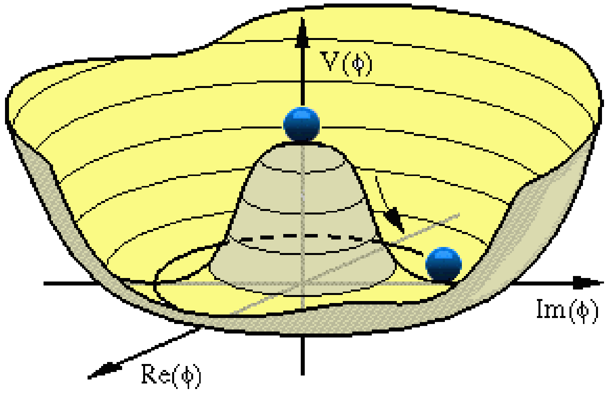
$$\langle 0|\Phi|0\rangle = \binom{0}{v/\sqrt{2}}$$

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

$$= 246 \text{ GeV}$$



- **– symmetric minimum: instable**
- **– true vaccum: degenerate**



⇒ to obtain the physical states,
write $\mathcal{L}_S$ with the true vacuum
(diagoalised fields/interactions).

2. The Higgs mechanism in the SM

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

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

$$= \frac{1}{2}\left|\begin{pmatrix} \partial_\mu - \frac{i}{2}(g_2W^3_\mu + g_1B_\mu) & -\frac{ig_2}{2}(W^1_\mu - iW^2_\mu) \\ -\frac{ig_2}{2}(W^1_\mu + iW^2_\mu) & \partial_\mu + \frac{i}{2}(g_2W^3_\mu - g_1B_\mu) \end{pmatrix}\binom{0}{v+H}\right|^2$$

$$= \frac{1}{2}(\partial_\mu H)^2 + \frac{1}{8}g_2^2(v+H)^2|W^1_\mu + iW^2_\mu|^2 + \frac{1}{8}(v+H)^2|g_2W^3_\mu - g_1B_\mu|^2$$

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

$$W^\pm = \frac{1}{\sqrt{2}}(W^1_\mu \mp W^2_\mu)\,,\ Z_\mu = \frac{g_2W^3_\mu - g_1B_\mu}{\sqrt{g_2^2+g_1^2}}\,,\ A_\mu = \frac{g_2W^3_\mu + g_1B_\mu}{\sqrt{g_2^2+g_1^2}}$$

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

2. The Higgs mechanism in the SM

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

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

⇒ 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: $v = 1/(\sqrt{2} G_F)^{1/2} \sim 246 \, \mathrm{GeV}$.

⇒ 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. The Higgs mechanism in the SM

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

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

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

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

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

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

The Higgs boson mass is given by: $\mathrm{M}_\mathrm{H}^2 = 2\lambda \mathrm{v}^2 = -2\mu^2$.

The Higgs triple and quartic self–interaction vertices are:

$$\mathrm{g}_{\mathrm{H}^3} = 3\mathrm{i}\,\mathrm{M}_\mathrm{H}^2/\mathrm{v}\,,\ \mathrm{g}_{\mathrm{H}^4} = 3\mathrm{i}\mathrm{M}_\mathrm{H}^2/\mathrm{v}^2$$

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

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

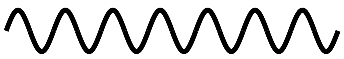
$$\mathcal{L}_{\mathrm{M_V}} \sim \mathrm{M}_\mathrm{V}^2(1+\mathrm{H}/\mathrm{v})^2\ ,\ \mathcal{L}_{\mathrm{m_f}} \sim -\mathrm{m_f}(1+\mathrm{H}/\mathrm{v})$$

$$\Rightarrow \mathrm{g}_{\mathrm{Hff}} = \mathrm{im_f}/\mathrm{v}\,,\ \mathrm{g}_{\mathrm{HVV}} = -2\mathrm{i}\mathrm{M}_\mathrm{V}^2/\mathrm{v}\,,\ \mathrm{g}_{\mathrm{HHVV}} = -2\mathrm{i}\mathrm{M}_\mathrm{V}^2/\mathrm{v}^2$$

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

2. The Higgs mechanism in the SM

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

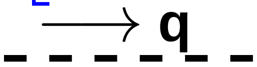


$\longrightarrow q$ $\quad \frac{-i}{q^2-M_V^2+i\epsilon}\left[g_{\mu\nu}+(\zeta-1)\frac{q_\mu q_\nu}{q^2-\zeta M_V^2}\right]$

$\zeta=\infty$: **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).**
- **Massive boson polarisations:** $\epsilon_\pm=\frac{1}{\sqrt{2}}(0,1,\pm \mathbf{i},0)$, $\epsilon_\mathbf{L}=\frac{1}{\mathbf{m}}(\mathbf{p_Z},0,0,\mathbf{E})$: **longitudinal polarisation dominates largely,** $\epsilon_\mathbf{L}\propto \mathbf{E}$, **at high energies..**
- **At very high energies,** $\sqrt{\mathbf{s}}\gg \mathbf{M_V}$, **a good approximation is** $\mathbf{M_V}\sim 0$. **The** $\mathbf{V_L}$ **components of V can be replaced by the Goldstones,** $\mathbf{V_L}\to\mathbf{w}$.
- **In fact, the electroweak equivalence theorem tells that at high energies, massive vector bosons are equivalent to Goldstones; in VV scattering eg:**

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

Thus, we can simply replace Vs by ws in the scalar potential and use ws:

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

3. Tests of the Standard Model

Electroweak fermions–gauge boson interactions described by symmetry:

$$\mathcal{L}_{\rm NC} = e J_\mu^{\rm A} A^\mu + \frac{g_2}{\cos\theta_W} J_\mu^{\rm Z} Z^\mu \; , \quad \mathcal{L}_{\rm CC} = \frac{g_2}{\sqrt{2}} (J_\mu^+ W^{+\mu} + J_\mu^- W^{-\mu})$$

$$J_\mu^{\rm A} = Q_f \bar{f} \gamma_\mu f \; , \; J_\mu^{\rm Z} = \frac{1}{4} \bar{f} \gamma_\mu [\hat{v}_f - \gamma_5 \hat{a}_f] f \; , \; J_\mu^+ = \frac{1}{2} \bar{f}_u \gamma_\mu (1-\gamma_5) f_d$$

with $v_f = \frac{\hat{v}_f}{4 s_W c_W} = \frac{2 I_f^3 - 4 Q_f s_W^2}{4 s_W c_W} \; , \; a_f = \frac{\hat{a}_f}{4 s_W c_W} = \frac{2 I_f^3}{4 s_W c_W}$

3families: complication in CC as current eigenstates $\neq$ mass eigenstates:

connected by a unitary transformation: $(d', s', b') = V_{\rm CKM}(d, s, b)$

$V_{\rm CKM} \equiv 3 \times 3$ unitarity matrix; NC are diagonal in both bases (GIM).

Parametrized by 3 angles and 1 CPV phase: great tests at c and b–factories

In the SM, there are 18 free parameters (ignoring strong CPV and ν sector):

- 3 lepton + 6 quark masses + 4 CKM parameters for quark interactions;
- 3 gauge couplings g_s, g_2, g_1 and 2 parameters μ, λ from scalar potential,

More precise inputs $\Rightarrow \alpha_s, \alpha(M_Z^2), G_F, M_Z$ and M_H (unknown until 2012).

M_W and $\sin^2\theta_W$ predicted: $\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha(M_Z^2)}{2M_W^2(1-M_W^2/M_Z^2)}; \; \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}.$

In fact, they are related by $\rho = \frac{M_W^2}{c_W^2 M_Z^2} \equiv 1$ at tree–level in the SM...

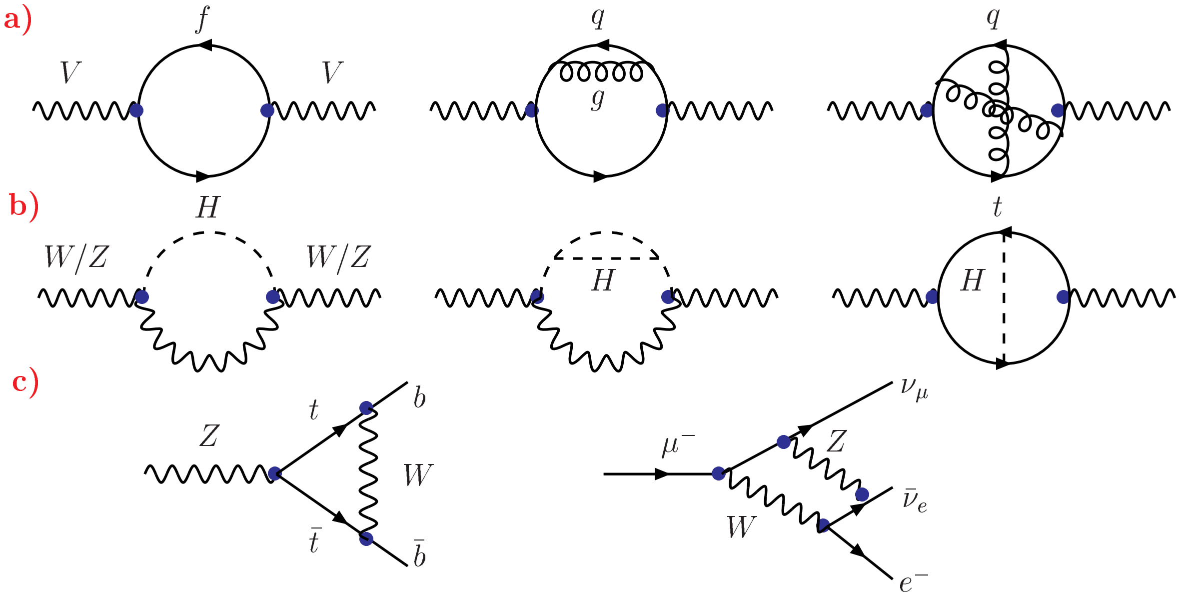
3. Tests of the SM: the gauge sector

To have precise predictions, include the EW+strong radiative corrections:

fermion contributions:
light $\propto \mathrm{Log} m_f/M_Z$
heavy $\propto m_t^2$

Higgs contributions:
$\propto \mathrm{Log} M_H/M_Z$

Direct corrections:
$\propto m_t^2, \mathrm{Log} m_f/M_Z$



The dominant corrections are to the running of α and the ρ parameter:

$$\Delta\alpha = \Pi_{\gamma\gamma}(M_Z^2) - \Pi_{\gamma\gamma}(0) \propto \frac{\alpha}{\pi}\log\frac{m_f^2}{M_Z^2} \Rightarrow \sigma(e^+e^- \to q\bar{q}) + \cdots$$

$$\rho = \frac{1}{1-\Delta\rho}\ , \ \Delta\rho = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2} = \frac{3G_\mu m_t^2}{8\sqrt{2}\pi^2} - \frac{G_\mu M_W^2}{8\sqrt{2}\pi^2}\log\frac{M_H^2}{M_W^2} + \cdots$$

- **Use** $\frac{1}{\alpha} = 128.95 \pm 0.03, G_\mu = 1.16637 \frac{10^{-5}}{\mathrm{GeV}^2}, M_Z = 91.187 \pm 0.002$**GeV**
- $\alpha_s = 0.1172 \pm 0.002$ **+ fermion masses with** $m_t = 171 \pm 1$**GeV from Tevatron;**

$\Rightarrow$ **predict:** $\Gamma_Z^{\rm tot}, \Gamma(Z \to f\bar{f}), A_{FB}^f, A_{LR}, A_{LR/FB}^f \equiv f(a_f, v_f) \Rightarrow \sin^2\theta_W$

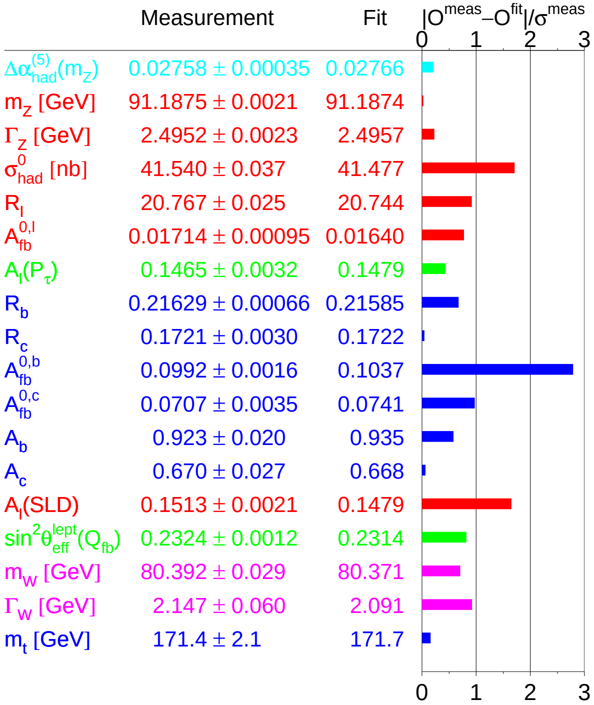
$\Rightarrow$ **predict** M_W **(and** Γ_W**) precisely measured at LEP2 and Tevatron.**

3. Tests of the SM: the gauge sector

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

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

- γ,Z to fermions couplings
- Z and W masses/properties
- α_S and QCD at LEP+Tevatron
- c,b,t quarks at quark factories
- many low energy experiments

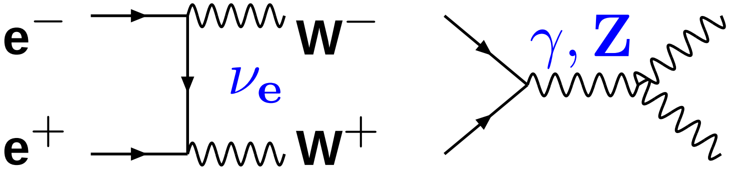


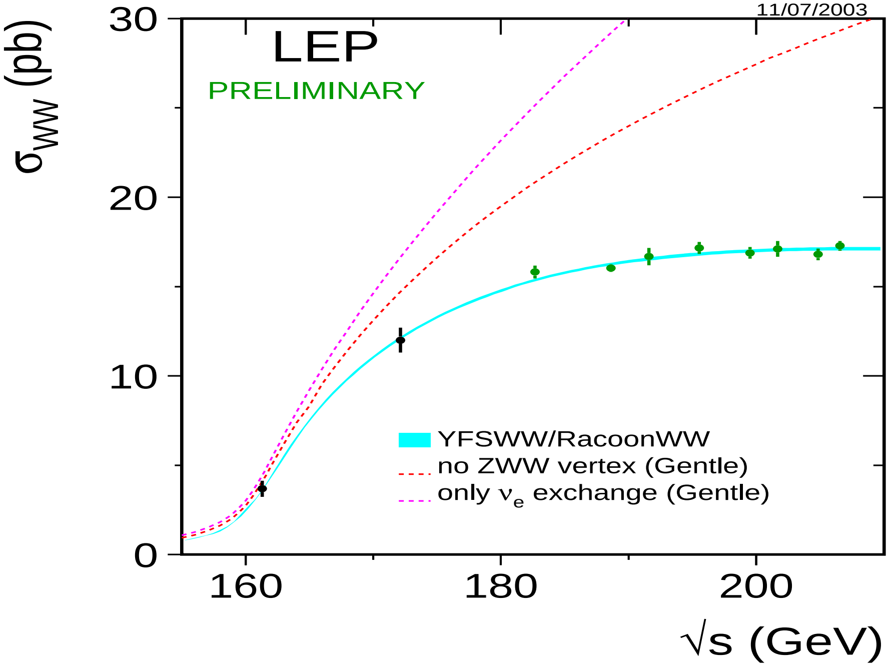
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	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

- **EW gauge structure tested@LEP2:**

self-couplings as dictated by SU(2)!





- **SU(3)/QCD structure also tested:**

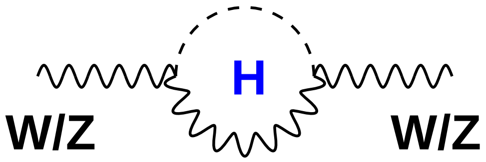
α_S running +gluon self couplings!

3. Tests of the SM: constraints on M_H

First, there were constraints from pre–LHC experiments: LEP, Tevatron...

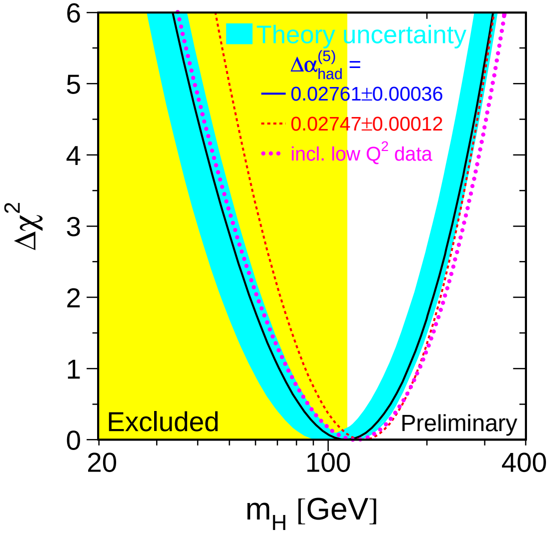
Indirect Higgs searches:

H contributes to RC to W/Z masses:



Fit the EW precision measurements:

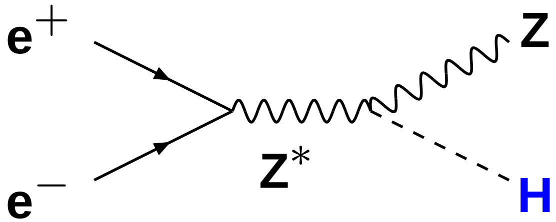
we obtain $M_H = 92^{+34}_{-26}$ GeV, or



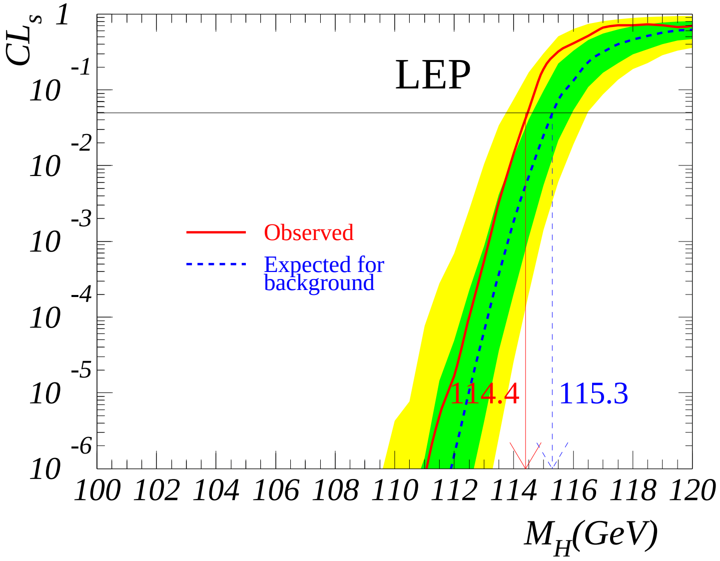
$M_H \lesssim 160$ GeV at 95% CL

Direct searches at colliders:

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



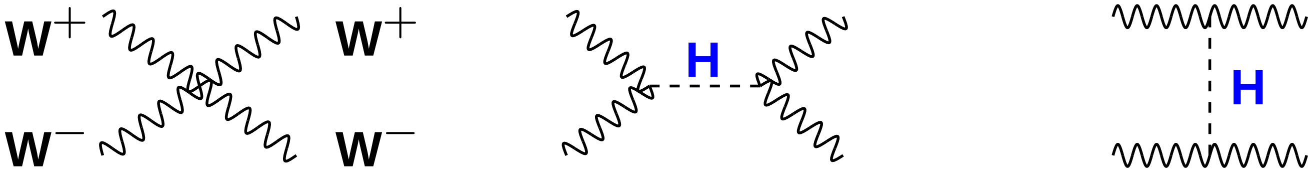
$M_H > 114.4$ GeV @95%CL



Tevatron $M_H \neq 160-175$ GeV

3. Tests of the SM: constraints on $\mathrm{M_H}$

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



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

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

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

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

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

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

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

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

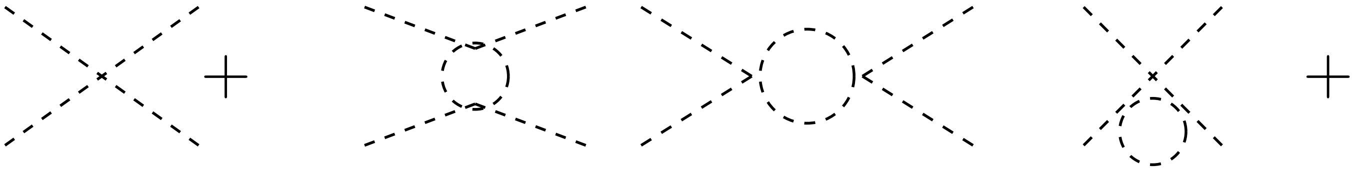
$$\mathrm{unitarity \Rightarrow \sqrt{s} \lesssim 1.7\ TeV\ \ (\sqrt{s} \lesssim 1.2\ TeV)}$$

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

3. Tests of the SM: constraints on M_H

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!)

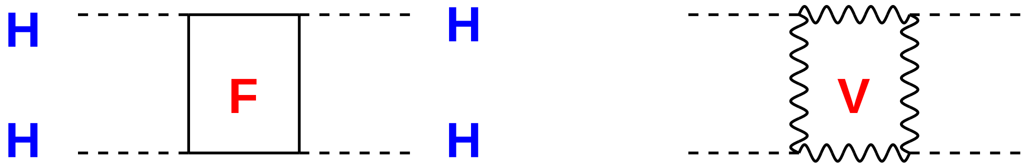
If $\Lambda_C = M_P,\ \lambda \lesssim 4\pi \Rightarrow M_H \lesssim 180$ GeV

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

3. Tests of the SM: constraints on M_H

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:

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

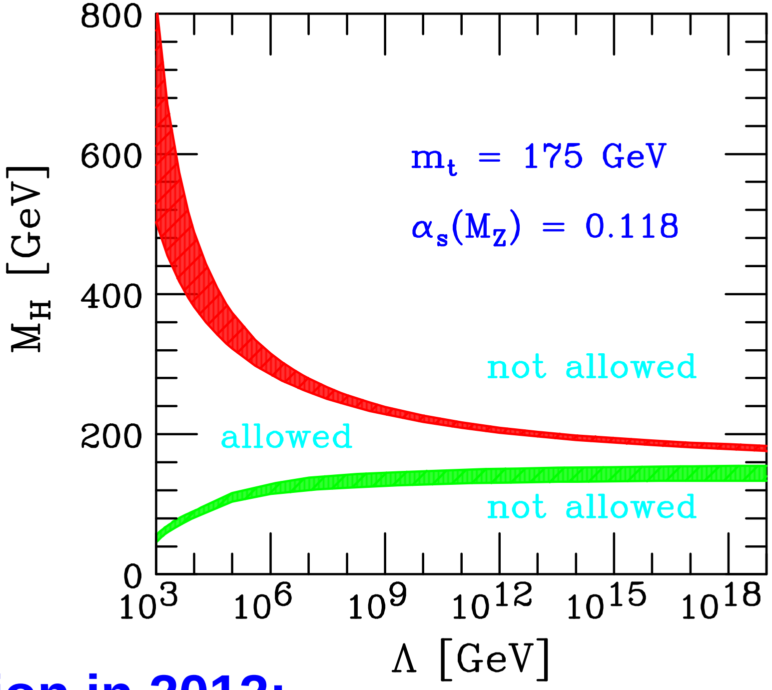
Very strong constraint: $Q = \Lambda_C \sim 1\,\mathrm{TeV} \ \Rightarrow M_H \gtrsim 70$ GeV

(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. Tests of the SM: constraints on M_H

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.

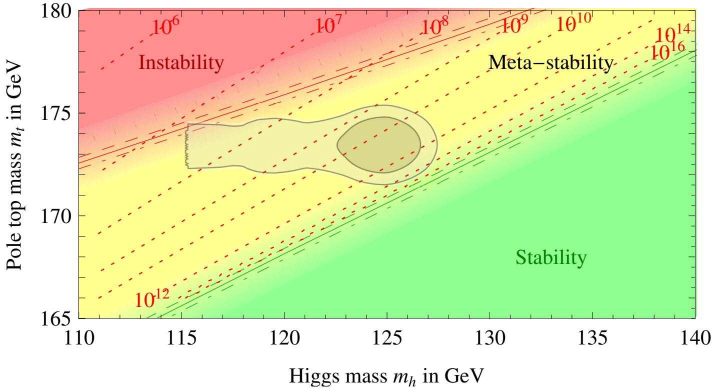
At 2–loop for m_t^{pole}=173.1 GeV:

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

but vacuum metastable below!

metastability OK: unstable vacuum

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

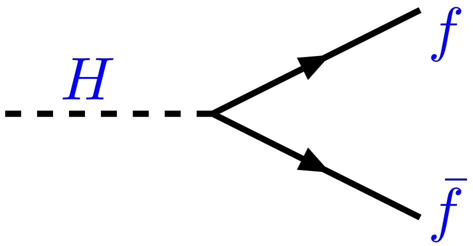


4. Higgs decays

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:



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

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

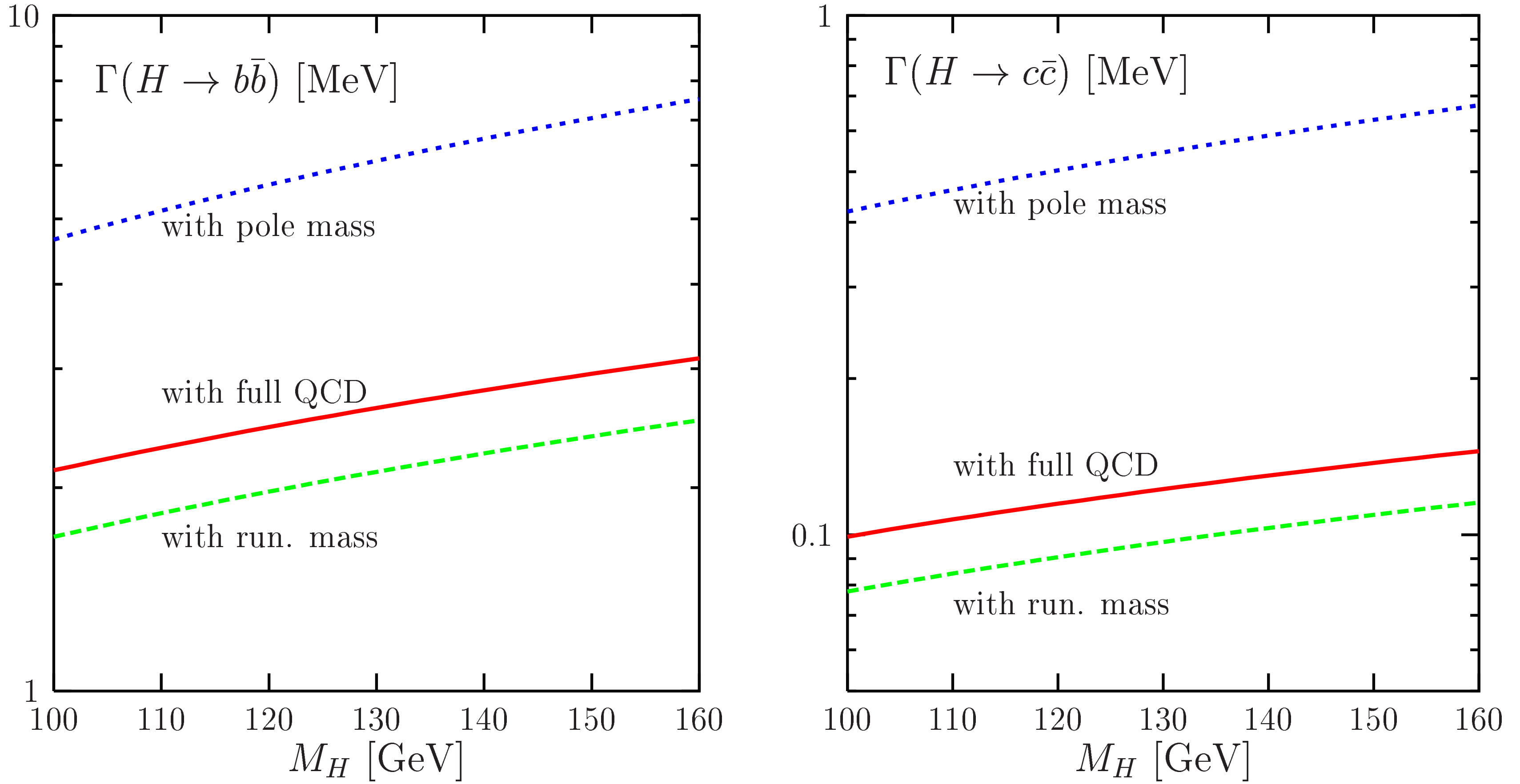
$$\mathrm{N_c} = \mathrm{color\ number}$$

- **Only $\mathrm{b\bar{b}, c\bar{c}}, \tau^+\tau^-, \mu^+\mu^-$ 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 with mass....**
- **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).**

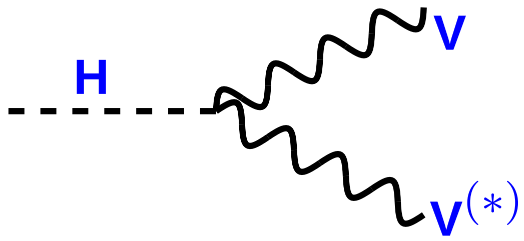
4. Higgs decays: fermions



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

Q	$\mathrm{m_Q}$	$\mathrm{\overline{m}_Q(m_Q)}$	$\mathrm{\overline{m}_Q(100\ GeV)}$
c	1.64 GeV	1.23 GeV	0.63 GeV
b	4.88 GeV	4.25 GeV	2.95 GeV

4. Higgs decays: massive gauge bosons



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

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

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

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

$\Gamma(\mathrm{H} \to \mathrm{WW}) = 2 \times \Gamma(\mathrm{H} \to \mathrm{ZZ}) \Rightarrow \mathrm{BR(WW)} \sim \frac{2}{3}, \mathrm{BR(ZZ)} \sim \frac{1}{3}$

$\Gamma(\mathrm{H} \to \mathrm{WW+ZZ}) \propto \frac{1}{2}\frac{M_H^3}{(1\ \mathrm{TeV})^3}$ 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, $\mathrm{H} \to \mathrm{VV}^* \to \mathrm{Vf\bar{f}}$.

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

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

4. Higgs decays: massive gauge bosons

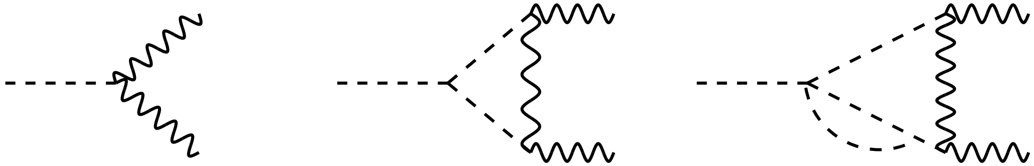
Electroweak radiative corrections to $H\to VV$:

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

$$\Gamma(H\to ZZ)\sim\Gamma(H\to w_0w_0)=\left(\frac{1}{2M_H}\right)\left(\frac{2!M_H^2}{2v}\right)^2\frac{1}{2}\left(\frac{1}{8\pi}\right)\to\frac{M_H^3}{32\pi v^2}$$

$H\to WW$: 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:



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

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

$M_H\sim\mathcal{O}(1\ \ \mathrm{TeV})\Rightarrow$ 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:

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

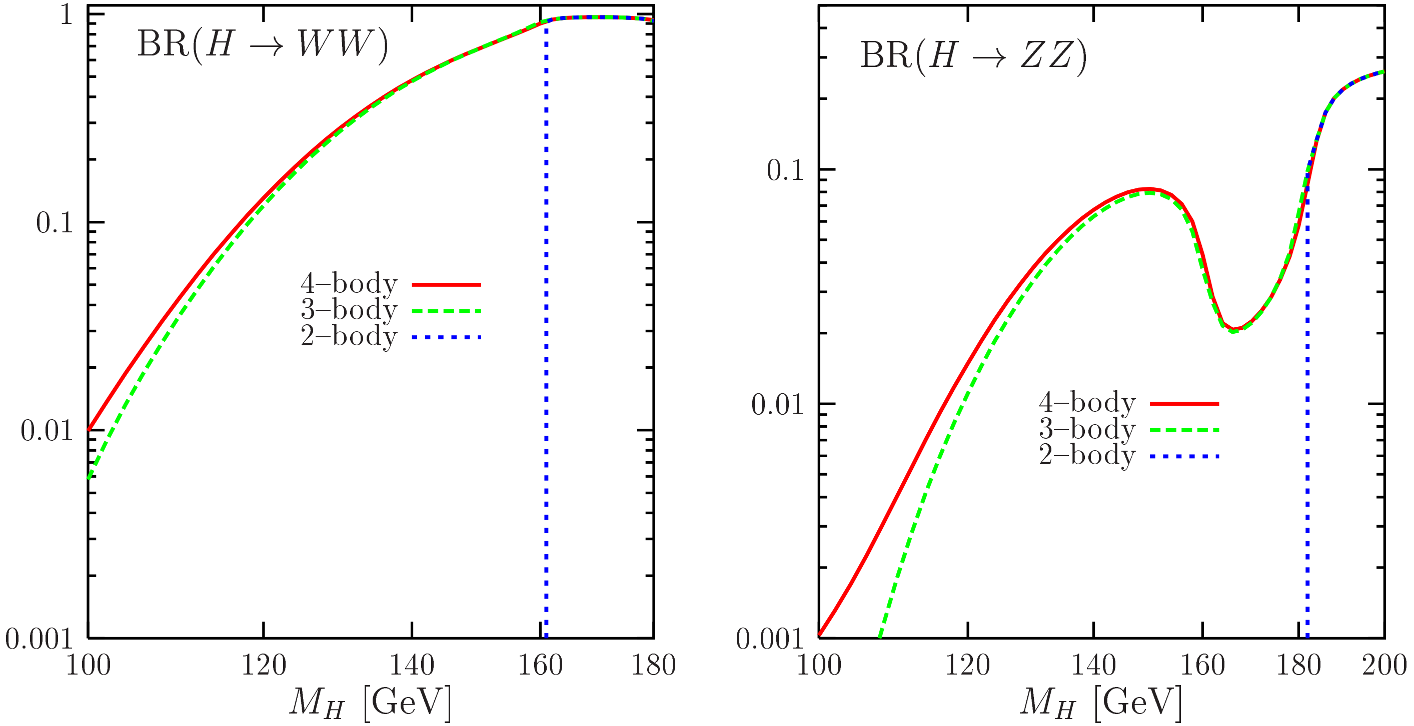
4. Higgs decays: massive gauge bosons

more convenient, 2+3+4 body decay calculation of $\mathrm{H}\to\mathrm{V}^*\mathrm{V}^*$:

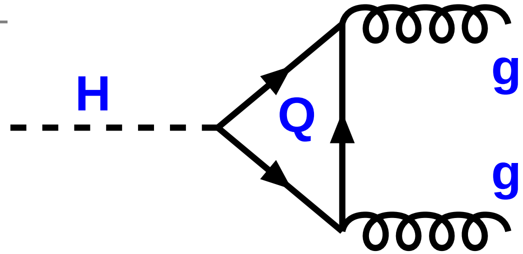
$$\boldsymbol{\Gamma(\mathrm{H}\to\mathrm{V}^*\mathrm{V}^*)=\frac{1}{\pi^2}\int_0^{\mathrm{M_H^2}}\frac{\mathrm{d}q_1^2\mathrm{M_V}\Gamma_\mathrm{V}}{(q_1^2-\mathrm{M_V^2})^2+\mathrm{M_V^2}\Gamma_\mathrm{V}^2}\int_0^{(\mathrm{M_H}-q_1)^2}\frac{\mathrm{d}q_2^2\mathrm{M_V}\Gamma_\mathrm{V}}{(q_2^2-\mathrm{M_V^2})^2+\mathrm{M_V^2}\Gamma_\mathrm{V}^2}\Gamma_0}$$

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

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



4. Higgs decays: 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.

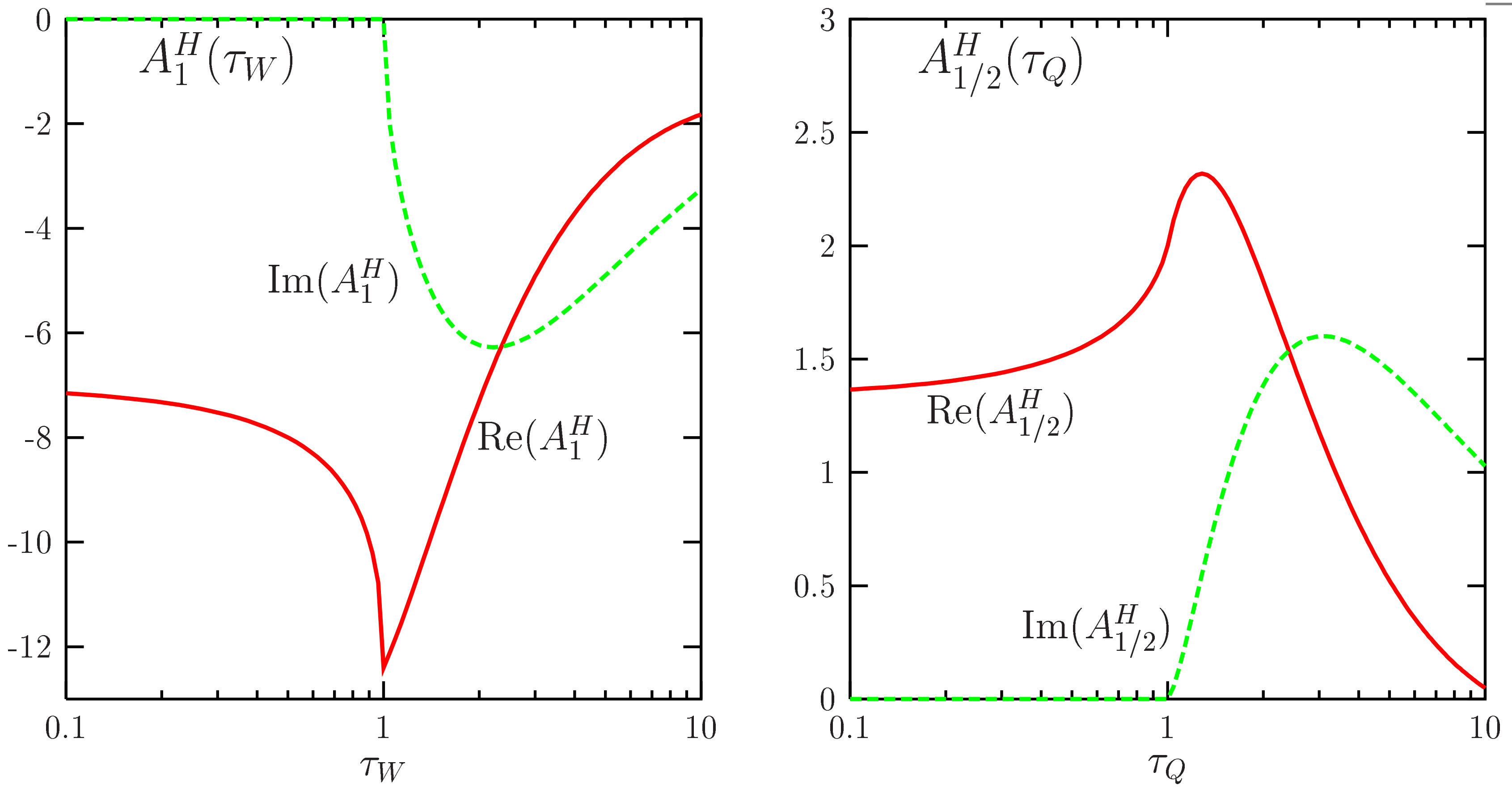
Good approximation in decay: include only t–loop with $m_Q \to \infty$.

- But very large QCD RC: two– and three–loops have to be included:

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

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

4. Higgs decays: gluons



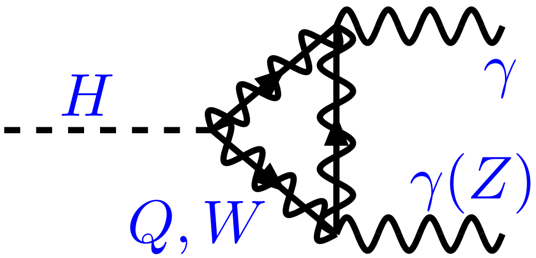
W and fermion amplitudes in $\mathrm{H}\to\gamma\gamma$ as function of $\tau_\mathrm{i}=\mathrm{M_H^2}/4\mathrm{M_i^2}$.

Trick for an easy calculation: low energy theorem for $\mathrm{M_H}\ll\mathrm{Mi}$:

– top loop: works very well for $\mathrm{M_H}\lesssim 2\mathrm{m_t}\approx 350$ GeV;

– W loop: works approximately for $\mathrm{M_H}\lesssim 2\mathrm{M_W}\approx 160$ GeV.

4. Higgs decays: 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: $\mathrm{BR}(\mathrm{H} \to \mathrm{X}) \equiv \frac{\Gamma(\mathrm{H}\to\mathrm{X})}{\Gamma(\mathrm{H}\to\mathrm{all})}$

- **’Low mass range’, $\mathrm{M_H} \lesssim 130$ GeV:**

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

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

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

- **’High mass range’, $\mathrm{M_H} \gtrsim 130$ GeV:**

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

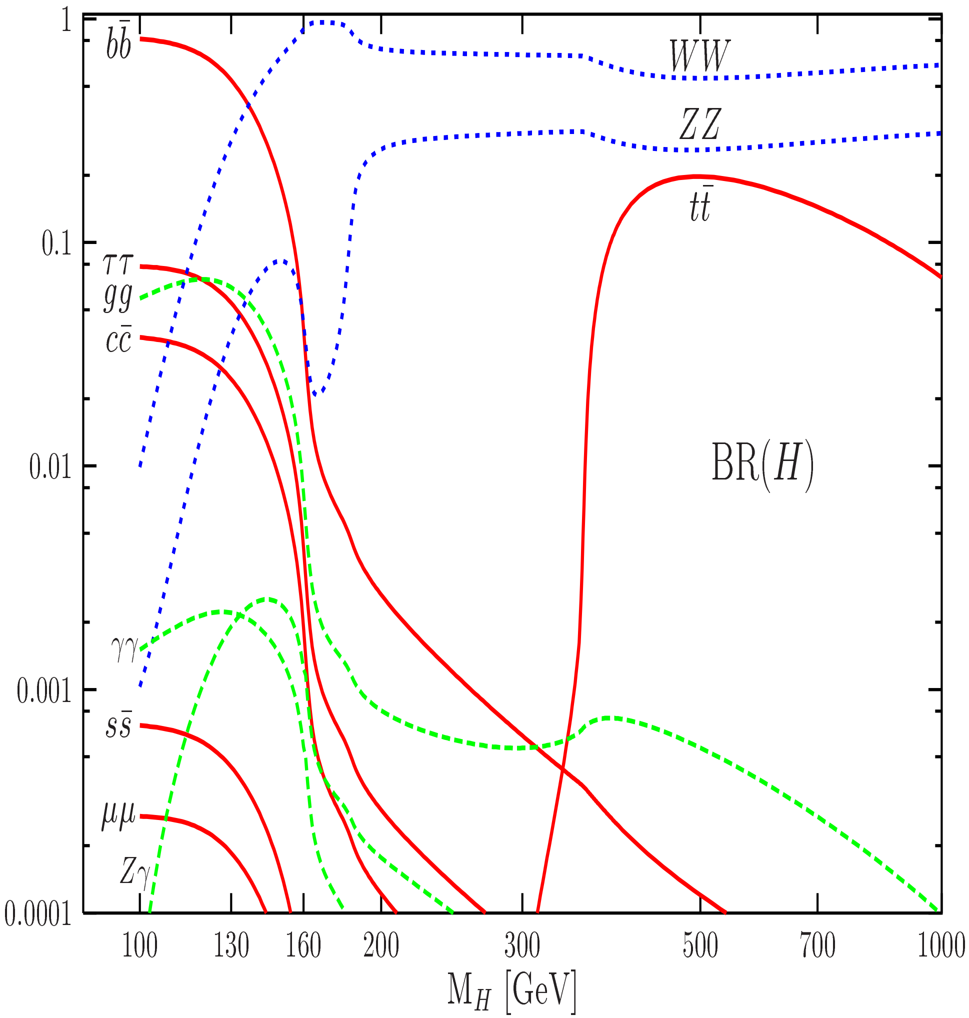
– $\mathrm{H} \to \mathrm{WW}, \mathrm{ZZ}$ **above (BR** $\to \frac{2}{3}, \frac{1}{3}$**)**

– $\mathrm{H} \to \mathrm{t\bar{t}}$ **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).**



HDECAY (AD, Spira, Kalinowski, 97-14)

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:**

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

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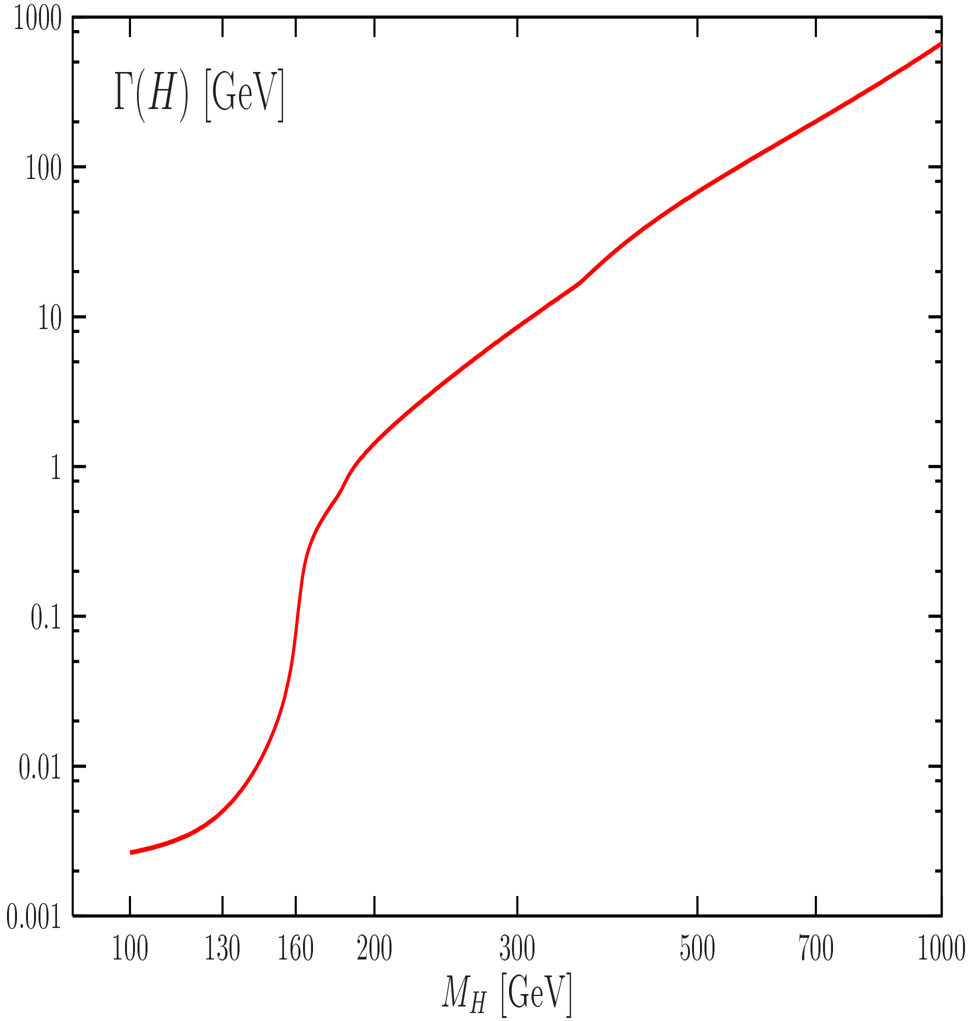
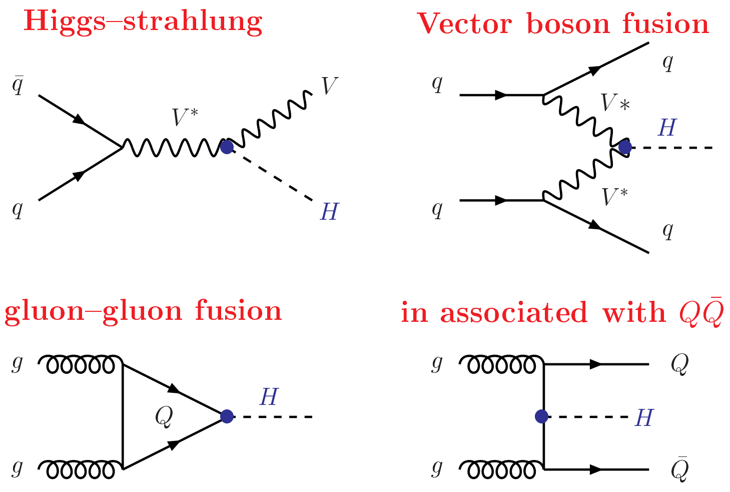
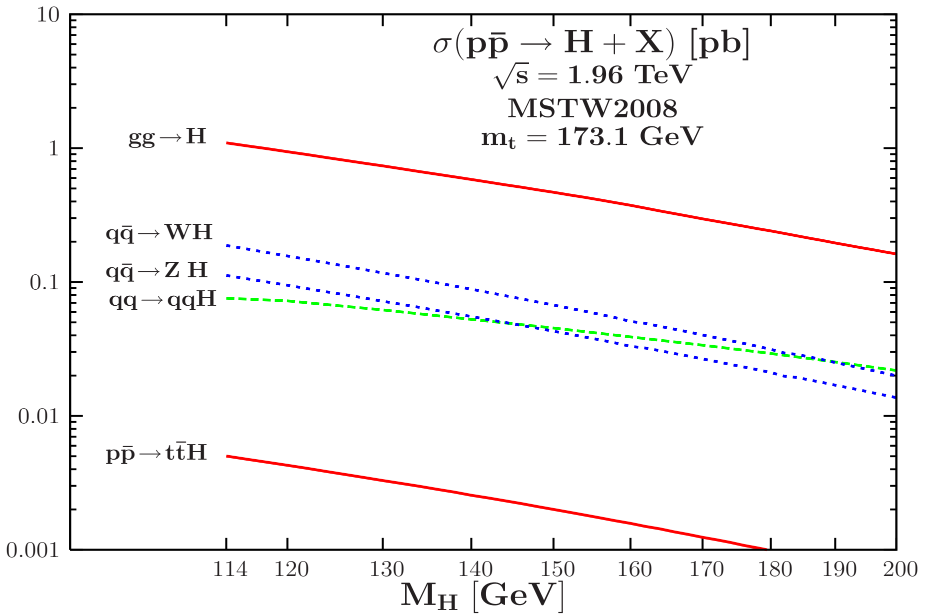


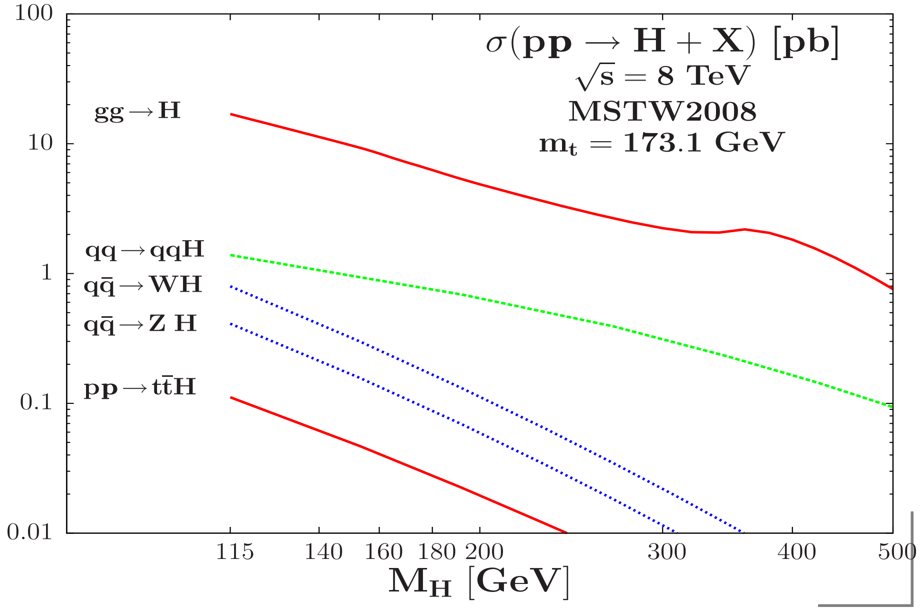
HDECAY (AD, Spira, Kalinowski, 97-14)

5. Higgs production hadron colliders

Main Higgs production channels







Large production cross sections

with gg$\to$ H by far dominant process

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

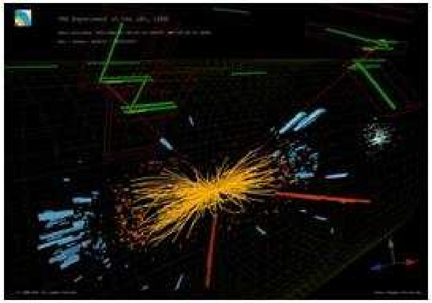
$\Rightarrow \mathcal{O}(10^3)$ events @Tevatron

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

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

5. Higgs production at hadron colliders

$\Rightarrow$ 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: $H \to \gamma\gamma, VV \to \ell$

– use specific kinematic features of Higgs

- Combine # decay/production channels

(and eventually several experiments...)

- Have a precise knowledge of S and B rates

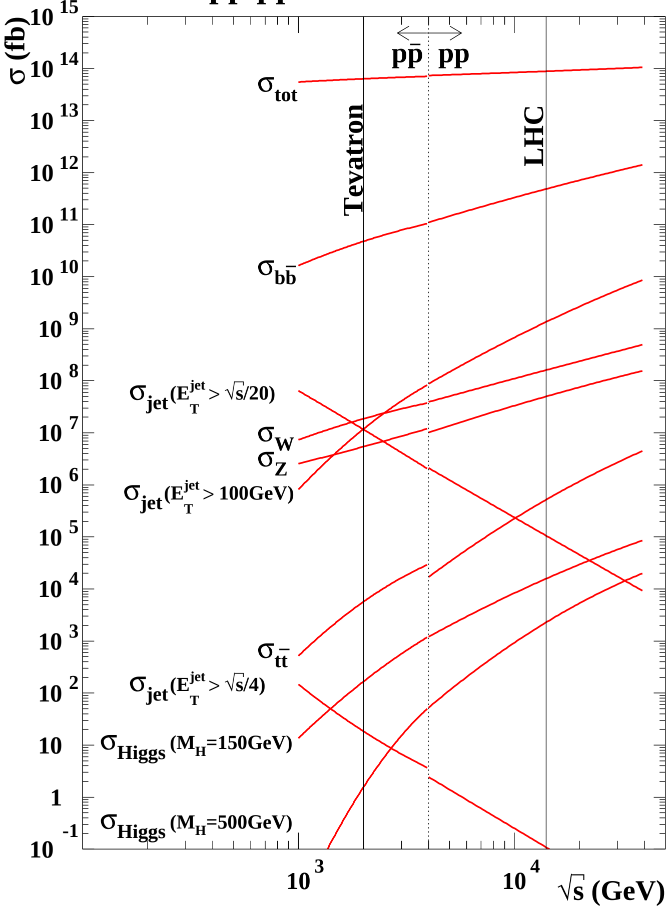
(higher orders can be factor of 2! see later)

- Gigantic experimental + theoretical efforts

(more than 30 years of very hard work!)

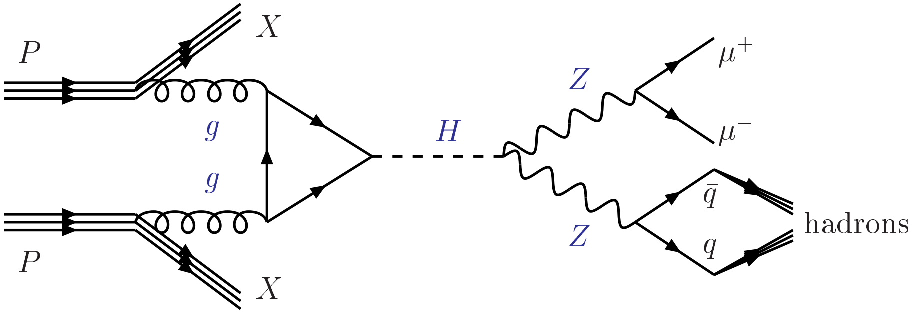
For a flavor of how it is complicated from the theory side: a look at the $gg \to H$ case...

pp/pp̄ cross sections



5. Higgs production at LHC

Best example of process at LHC to see how things work: $\mathrm{gg} \to \mathrm{H}$.



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

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: the two can factorise in production at a scale $\mu_{\mathbf{F}}$.

The partonic cross section of the subprocess, $\mathrm{gg} \to \mathrm{H}$, given by:

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

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

Convolute with gluon densities to obtain total hadronic cross section

$$\sigma = \int_{\mathbf{0}}^{\mathbf{1}} \mathrm{d}\mathbf{x_1} \int_{\mathbf{0}}^{\mathbf{1}} \mathrm{d}\mathbf{x_2} \frac{\pi^{\mathbf{2}}\mathbf{M_H}}{\mathbf{8\hat{s}}} \mathbf{\Gamma}(\mathbf{H} \to \mathbf{gg})\mathbf{g}(\mathbf{x_1})\mathbf{g}(\mathbf{x_2})\delta(\hat{\mathbf{s}} - \mathbf{M_H^2})$$

5. Higgs production at LHC: premices

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,
⇒ dependence on renormalisation/factorisations scales $\mu_{\rm R}/\mu_{\rm F}$.

● Choose a (natural scale) which absorbs/resums the large logs,
⇒ higher orders provide stability against $\mu_{\rm R}/\mu_{\rm F}$ scale variation.

● Since we truncate pert. series: only NLO/NNLO corrections available.
⇒ not known HO (hope small) 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.

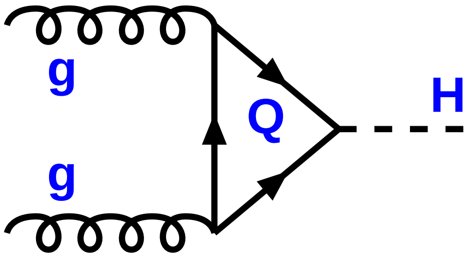
● In fact, one has to do this for both the signal and background (unless directly measurable from data): the important quantity is ${\rm s} = {\rm N_S}/\sqrt{\rm N_B}$.

⇒ a lot of theoretical work is needed!

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

5. Higgs production at LHC: gg fusion

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



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

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

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. Higgs production at LHC: 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.

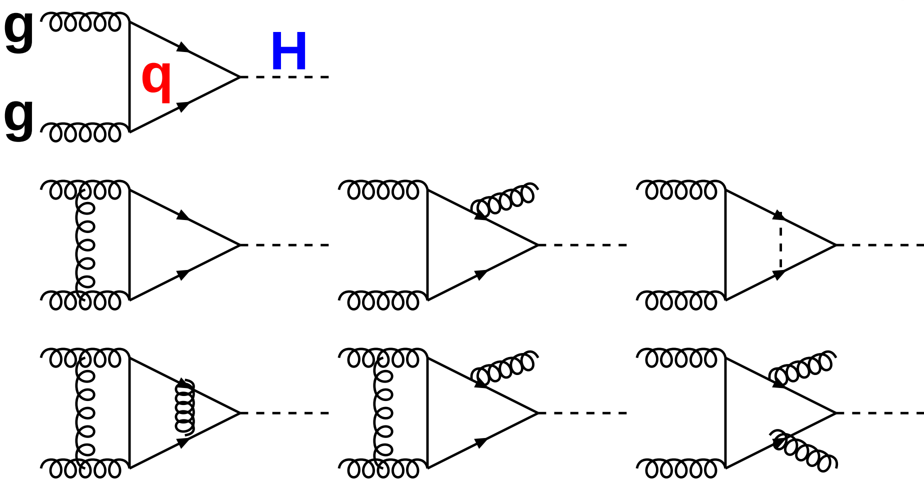
[g] Gambino+AD; Degrassi et al.

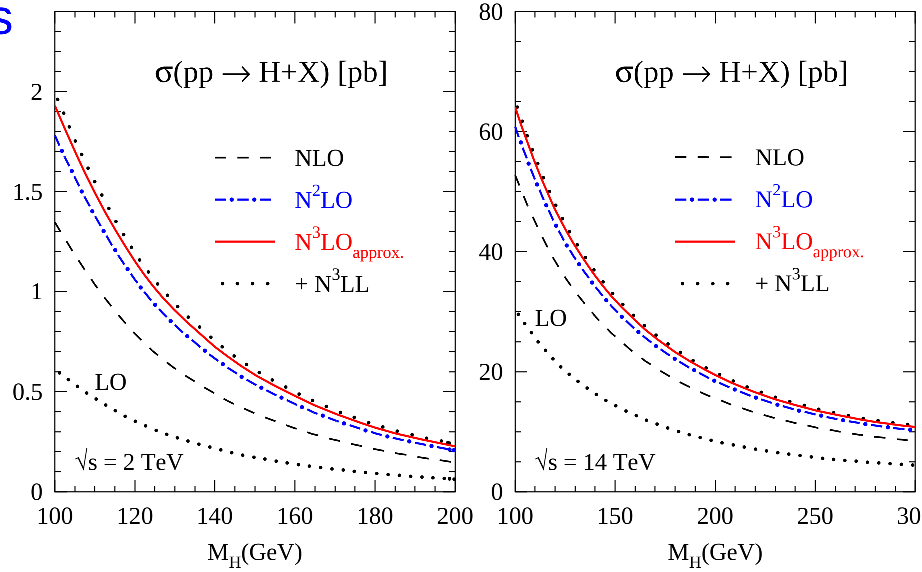
[h] Actis+Passarino+Sturm+Uccirati

[i] Anastasiou+Boughezal+Pietriello

[j] Anastasiou et al.; Grazzini

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





Moch+Vogt

5. Higgs production at LHC: 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.

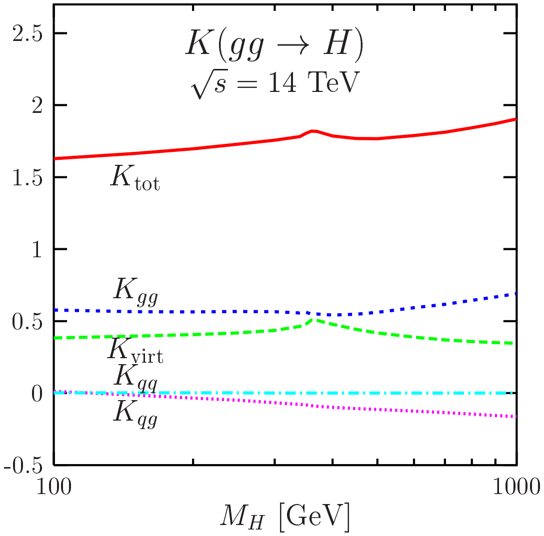
- Corrections have been calculated in $\mathrm{m_t} \to \infty$ limit beyond NLO.

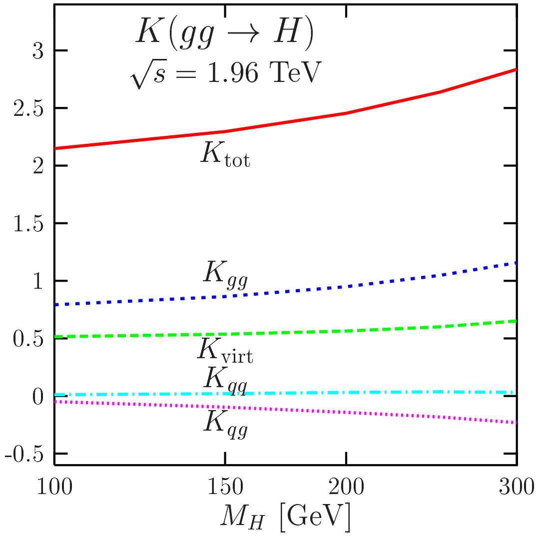
– moderate increase at NNLO by 30% and stabilisation with scales...

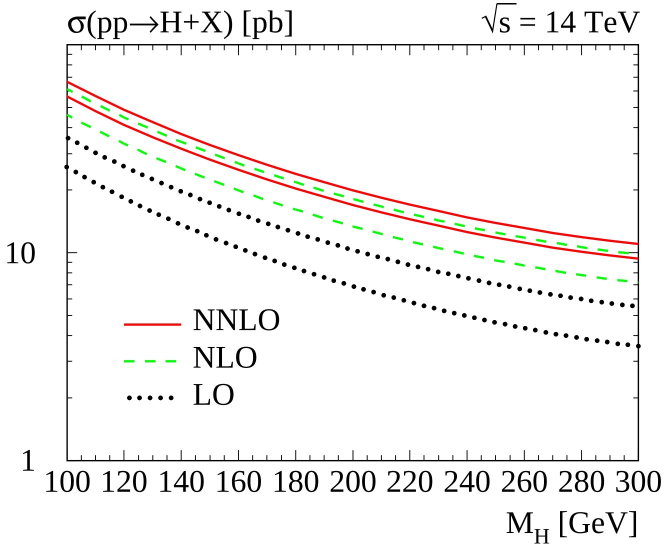
– soft–gluon resummation performed up to NNLL: $\approx$ 5–10% effects.

Note 1: NLO corrections to $\mathrm{P_T}, \eta$ distributions are also known.

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







5. Higgs production at LHC: gg fusion

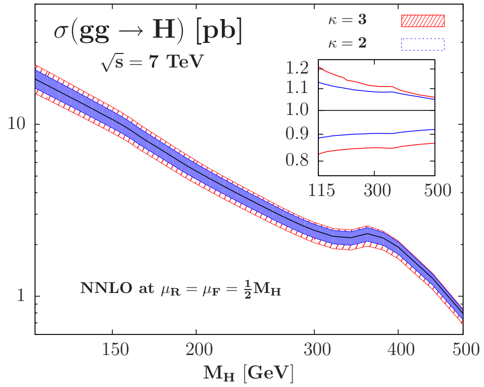
Despite of that, the $gg \to H$ cross section still affected by uncertainties

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

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

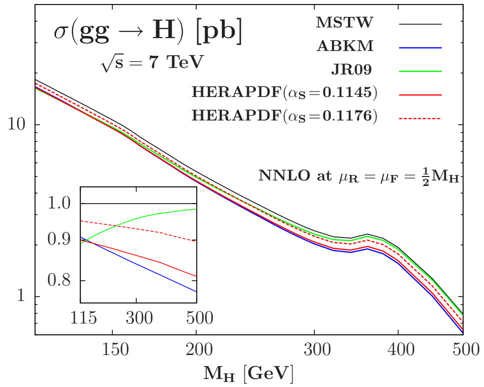
$$\mu_0/\kappa \leq \mu_R, \mu_F \leq \kappa\mu_0$$

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



- **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: $\Delta_{\rm pdf} \approx 10\%$@lHC



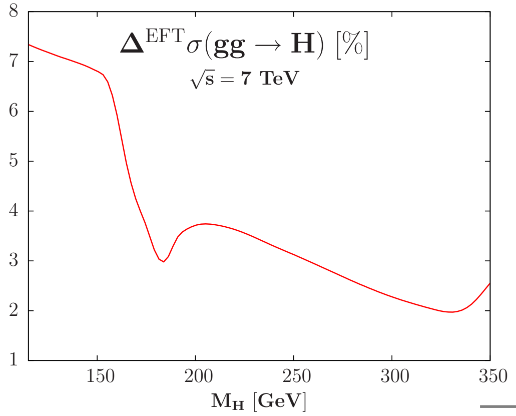
- **Uncertainty from EFT approach at NNLO**

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

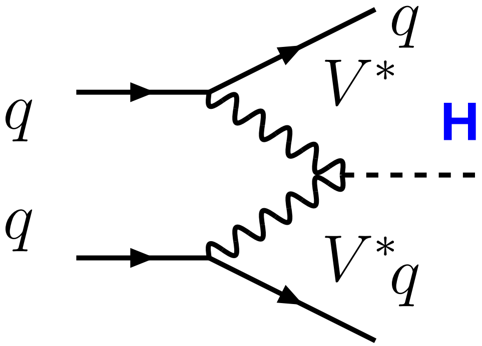
- **Include ΔBR(H$\to$X) of at most few %**

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

LHC-HxsWG; Baglio+AD $\Rightarrow$



5. Higgs production at LHC: VV fusion



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

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

Three–body final state: analytical expression rather complicated...
Simple form in LVBA: σ related to $\Gamma(\mathrm{H} \to \mathbf{VV})$ and $\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\tau}|_{\mathbf{V_L V_L/qq}}$.
Not too bad approximation at $\sqrt{\hat{\mathrm{s}}} \gg \mathrm{M_H}$: a factor 2 of accurate.
Large cross section: in particular for small $\mathrm{M_H}$ and large c.m. energy:

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

NLO 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!

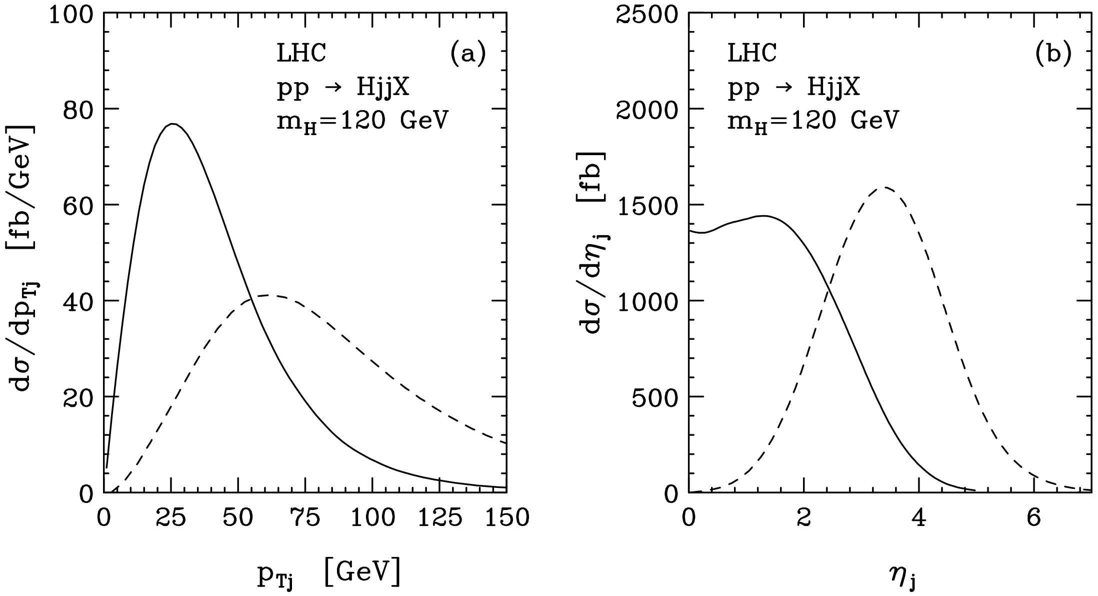
– NNLO corrections recently calculated in this scheme: very small.
– EW corrections are also small, of order of a few %.

5. Higgs production at LHC: VV fusion

Kinematics of the process: very specific for scalar particle production....

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

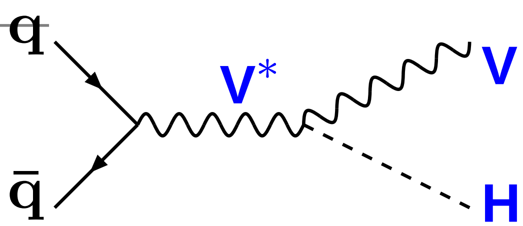
$\Rightarrow$ allows to suppress backgrounds to the level of H signal: $\rm S/B \sim 1$.



—– lowest/central jet **– – highest/central jet**

However, the various VBF cuts make the signal theoretically less clean:
– dependence on many cuts and variables, impact of HO less clear,
– contamination from the $\rm gg \to H+jj$ process not so small...

5. Higgs production at LHC: associated HV



$$\hat{\sigma}_{\rm LO} = \frac{G_\mu^2 M_V^4}{288\pi\hat{s}} \times (\hat{v}_q^2 + \hat{a}_q^2)\lambda^{1/2}\frac{\lambda+12M_V^2/\hat{s}}{(1-M_V^2/\hat{s})^2}$$

Similar to $e^+e^- \to HZ$ for Higgs@LEP2.

$\hat{\sigma} \propto \hat{s}^{-1}$ sizable only for $M_H \lesssim 200$ GeV.

At both LHC/Tevatron: $\sigma(W^\pm H) \approx \sigma(ZH)$.

In fact, simply Drell–Yan production of virtual boson with $q^2 \neq M_V^2$:

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

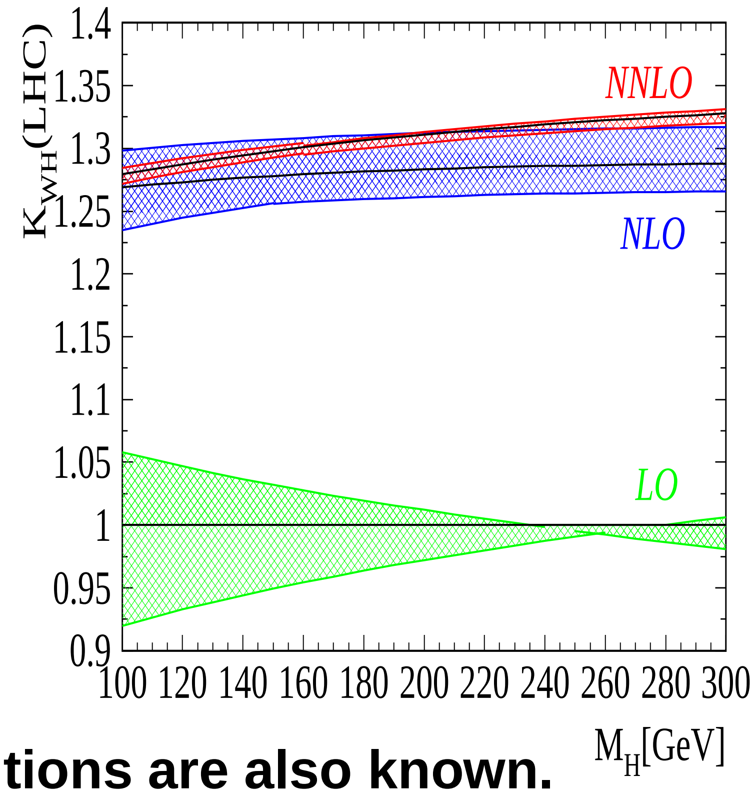
RC ⇒ those of known DY process

(2-loop: $gg \to HZ$ in addition).

QCD RC in HV known up to NNLO

(borrowed from Drell-Yan: K≈ 1.4)

EW RC known at $\mathcal{O}(\alpha)$: very small.



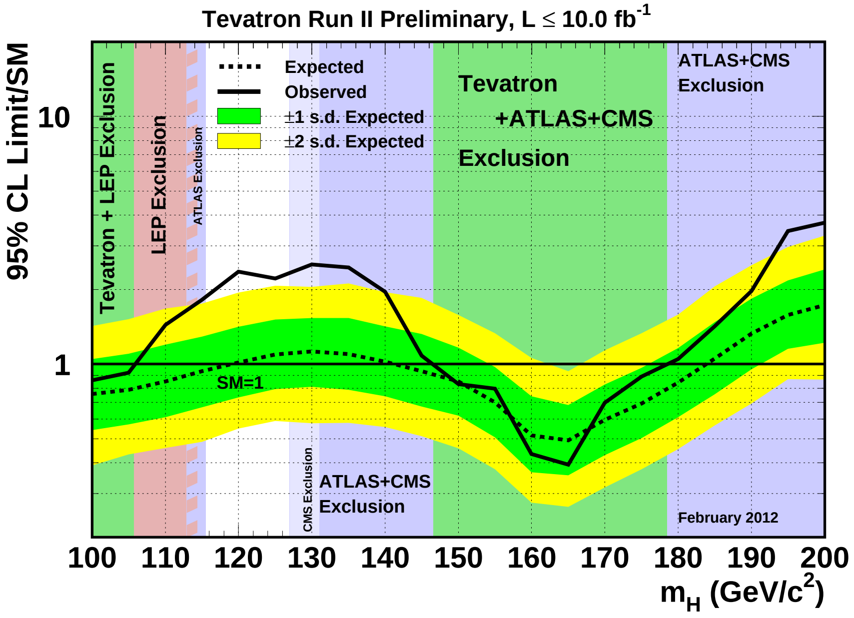
- **Radiative corrections to various distributions are also known.**
- **Process fully implemented in various MC programs used by experiment**

5. Higgs production at LHC: associated HV

Up-to-now, it plays a marginal role at the LHC (not a discover channel..).
Interesting topologies: $\mathrm{WH}\to\gamma\gamma\ell, \mathrm{b\bar{b}}\ell, 3\ell$ and $\mathrm{ZH}\to\ell\ell\mathrm{b\bar{b}}, \nu\nu\mathrm{b\bar{b}}$.
At high Higgs $\mathrm{P_T}$: one can use 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 clean channel esp. when normalized to $\mathrm{pp}\to\mathrm{Z}$: precision process!

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

$\approx$3σ excess for $\mathrm{M_H}=$115–135 GeV at the end of the Tevatronn run!

5. Higgs production at LHC: Htt production

Most complicated process for Higgs production at hadron colliders:

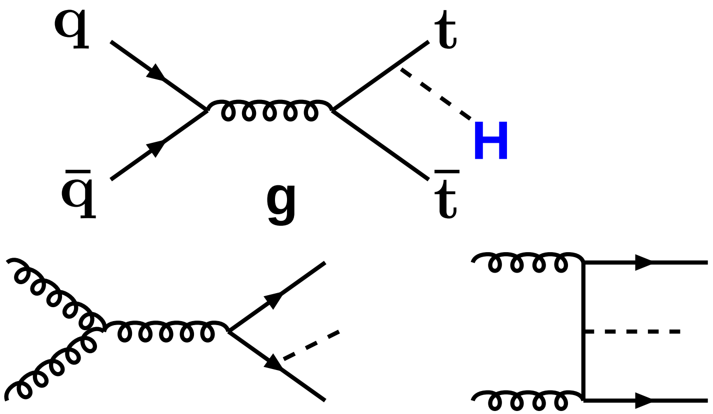
– qq and gg initial states channels

– three-body massive final states.

– at least 8 particles in final states..

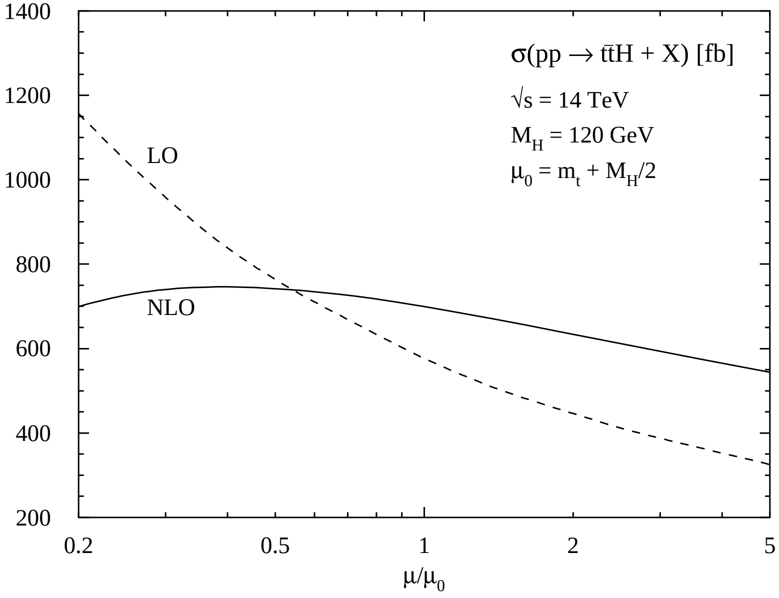
– small Higgs production rates

– very large ttjj+ttbb backgrounds.



NLO QCD corrections calculated:
small K–factors $(\approx$ 1–1.2)
strong reduction of scale variation!

Small corrections to kinematical distributions (e.g: $\mathrm{p_T^{top}}, \mathrm{P_T^H}$), etc...
Small uncertainties from HO, PDFs.



Processes with heavy quarks in BSM:

– Single top+Higgs: $\mathrm{pp \to tH+X}$.

– Production with bs: $\mathrm{pp \to bbH}$.

- Important for Htt Yukawa coupling!
- Interesting final states: $\mathrm{pp \to Htt \to \gamma\gamma + X}, \nu\nu\ell^\pm\ell^\mp, \mathrm{b\bar{b}}\ell^\pm$.
- Possibility for a 5 signal at $\mathrm{M_H} \lesssim 140$ GeV at high luminosities.

5. Higgs production at LHC: Htt production

Last expectations of ATLAS/CMS...)

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

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

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

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

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

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

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

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

Tevatron had still some data to analyze

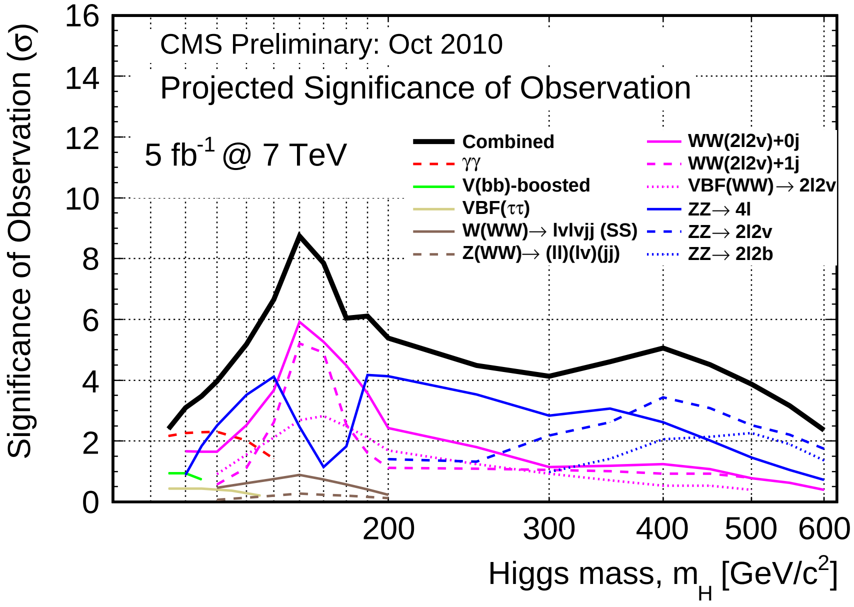
$HV \rightarrow b\bar{b}\ell X @ M_H \lesssim$130 GeV!!

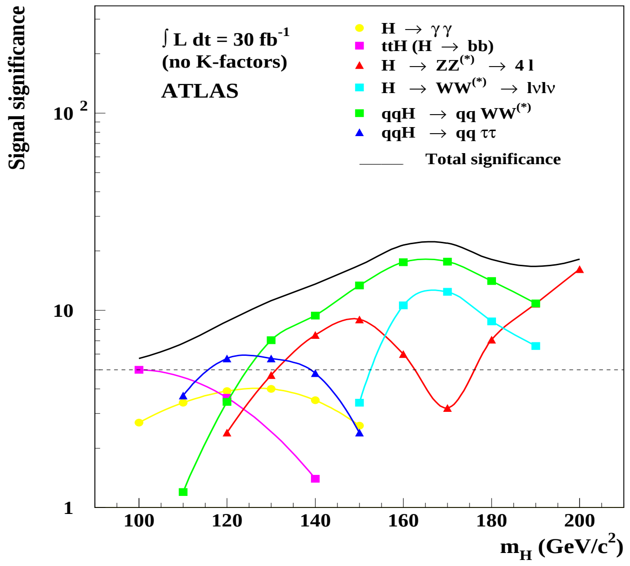
Full LHC: same as lHC plus some others

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

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

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

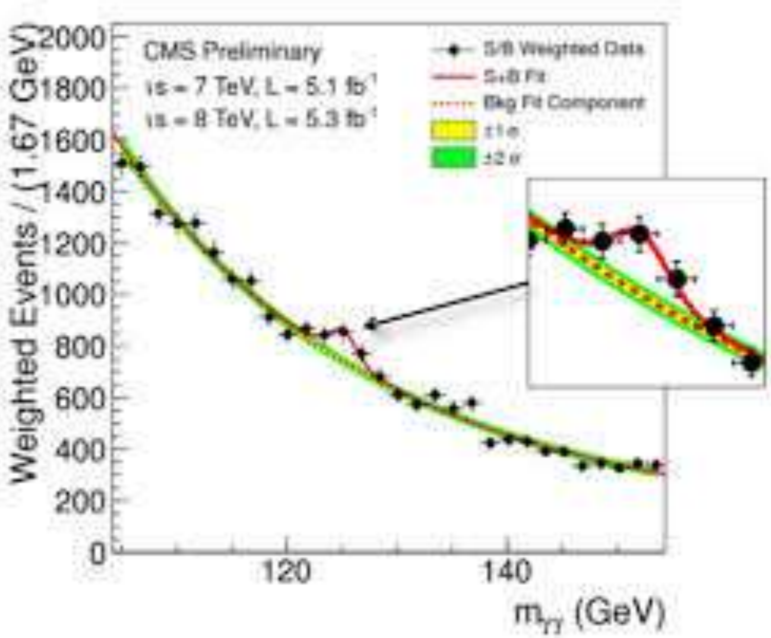


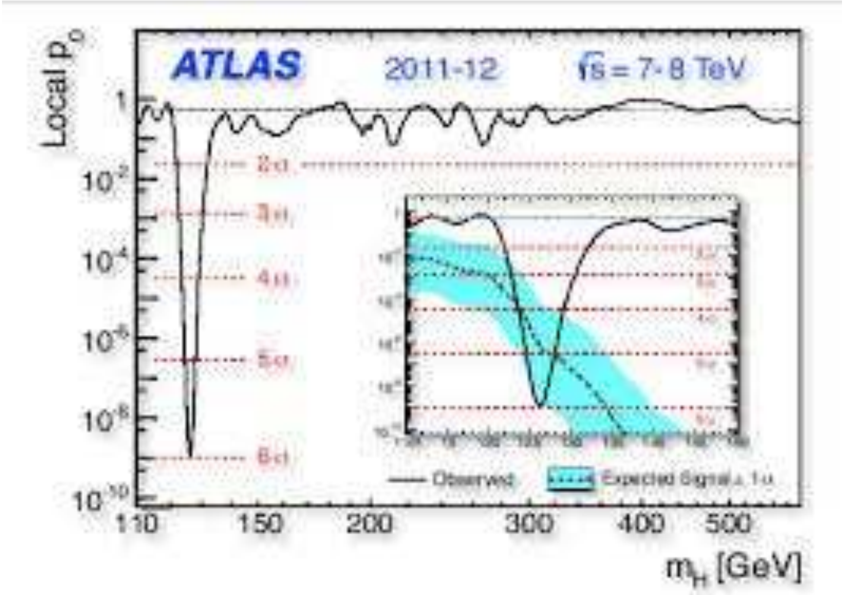


Conclusion? Mission accomplie!

6. Implications of the discovery

Discovery: a challenge met the 4th of July 2012: a Higgstorical day.





6. Implications of the discovery

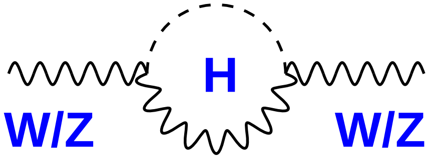
And the observed new state looks the long sought SM Higgs boson:

a triumph for high-energy physics!

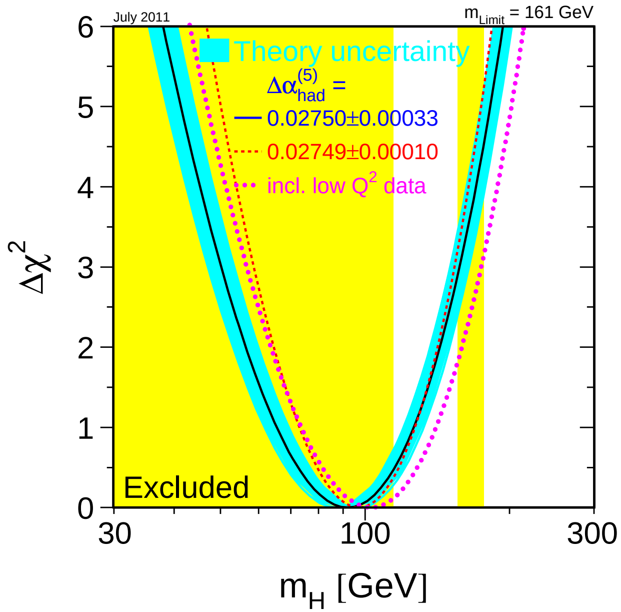
Indeed, constraints from EW data:

H contributes to the W/Z masses

through tiny quantum fluctuations



$$\propto \frac{\alpha}{\pi} \log \frac{M_H}{M_W} + \cdots$$



Fit the EW ($\lesssim$ 0.1%) precision data,

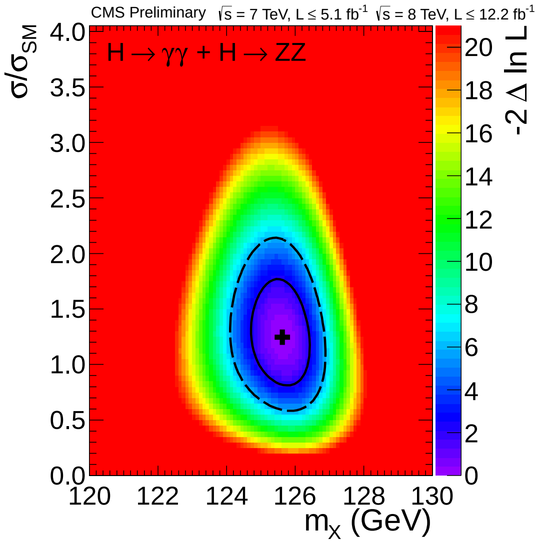
with all other SM parameters known,

one obtains $M_H = 92^{+34}_{-26}$ GeV, or

$$M_H \lesssim 160 \text{ GeV at 95\% CL}$$

versus "observed" $M_H = 125$ GeV.

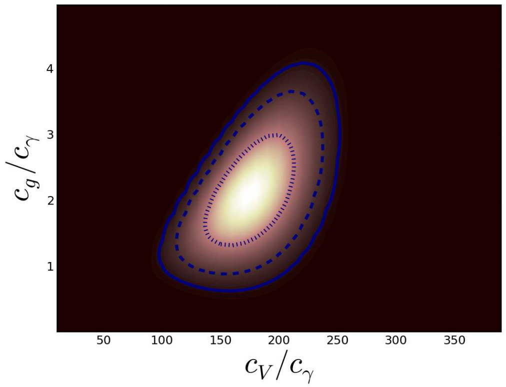
A very non–trivial check of the SM!



The SM is indeed a very successful theory, tested at the permille level...

6. Implications of the discovery

But lets check it is indeed a Higgs!



Spin: the state decays into $\gamma\gamma$

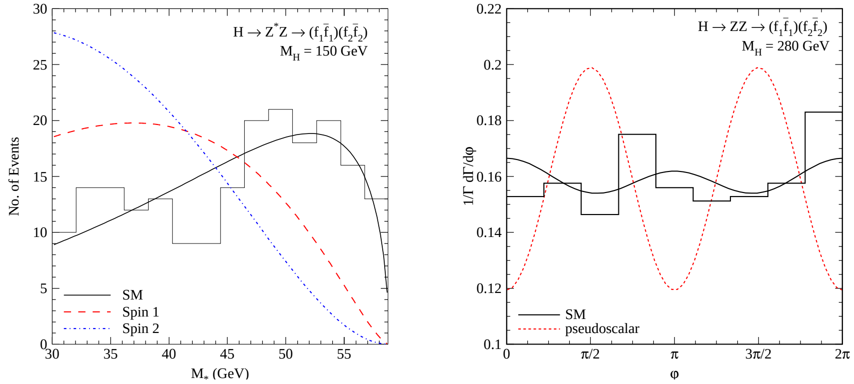
- not spin–1: Landau–Yang
- could be spin–2 like graviton? Ellis et al.

– miracle that couplings fit that of H,

– “prima facie” evidence against it:

e.g.: $c_g \neq c_\gamma, c_V \gg 35c_\gamma$

many th. analyses (no suspense...)

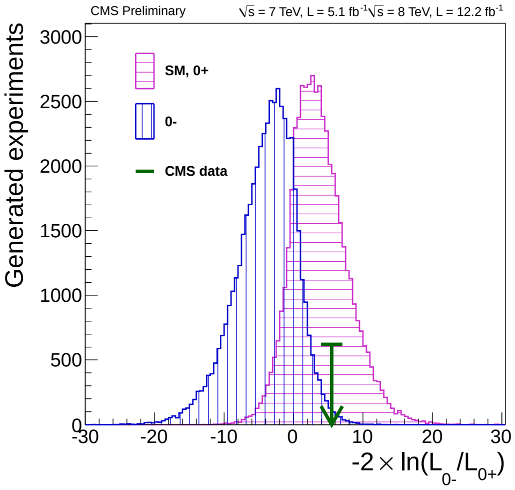


CP no: even, odd, or mixture?

(more important; CPV in Higgs!)

ATLAS and CMS CP analyses for

pure CP–even vs pure–CP–odd



$HV_\mu V^\mu$ versus $H\epsilon^{\mu\nu\rho\sigma}Z_{\mu\nu}Z_{\rho\sigma}$

$$\Rightarrow \frac{d\Gamma(H\to ZZ^*)}{dM_*} \text{ and } \frac{d\Gamma(H\to ZZ)}{d\phi}$$

MELA $\approx 3\sigma$ for CP-even..

6. Implications of the discovery

There are however some problems with this (too simple) picture:

– a pure CP odd Higgs does not couple to VV states at tree–level

– coupling should be generated by loops or HOEF: should be small

– H CP–even with small CP–odd admixture: high precision measurement..

– in H→VV only CP–even component projected out in most cases!

Indirect probe: through μ_{VV}

$$g_{HVV} = c_V g_{\mu\nu} \text{ with } c_V \leq 1$$

better probe: $\hat{\mu}_{ZZ} = 1.1 \pm 0.4!$

gives upper bound on CP mixture:

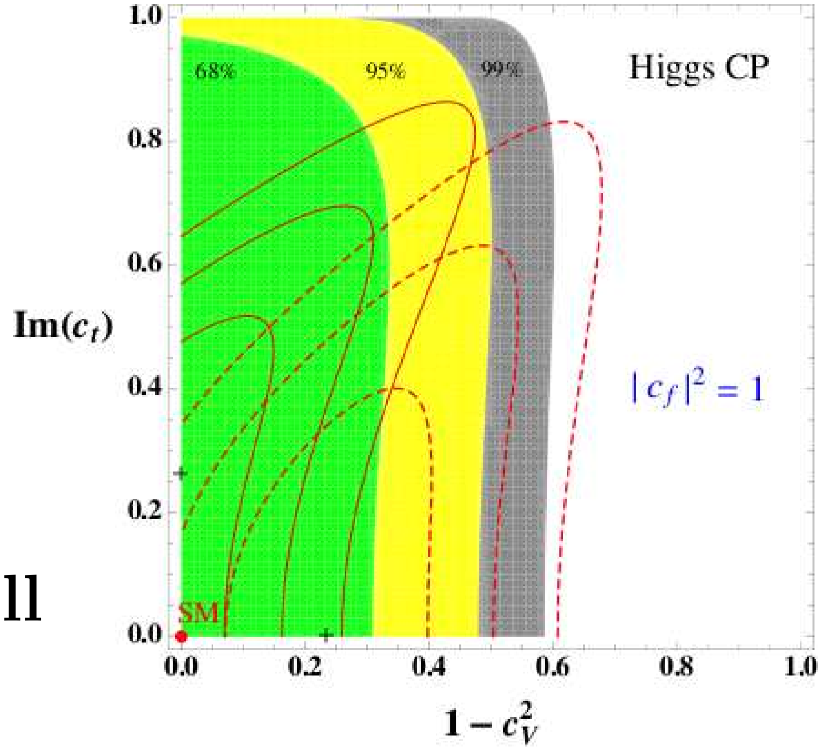
$$\eta_{CP} \equiv 1 - c_V^2 \gtrsim 0.5@68\%CL$$

Direct probe: g_{Hff} more democratic

$\Rightarrow$ processes with fermion decays.

spin-corelations in $q\bar{q} \to HZ \to b\bar{b}ll$

or later in $q\bar{q}/gg \to Ht\bar{t} \to b\bar{b}t\bar{t}$.



Extremely challenging even at HL-LHC...

Moreau...

6. Implications of the discovery

$\sigma\times$BR rates compatible with those expected in the SM

Fit of all LHC Higgs data ⇒

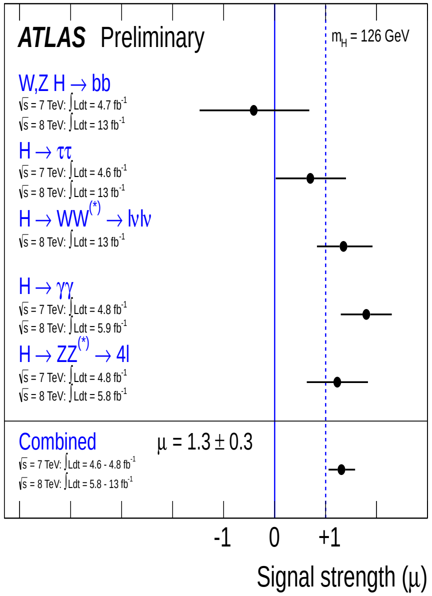
$\mu^{\rm signal}_{\rm strength}$=observ./SM rate:

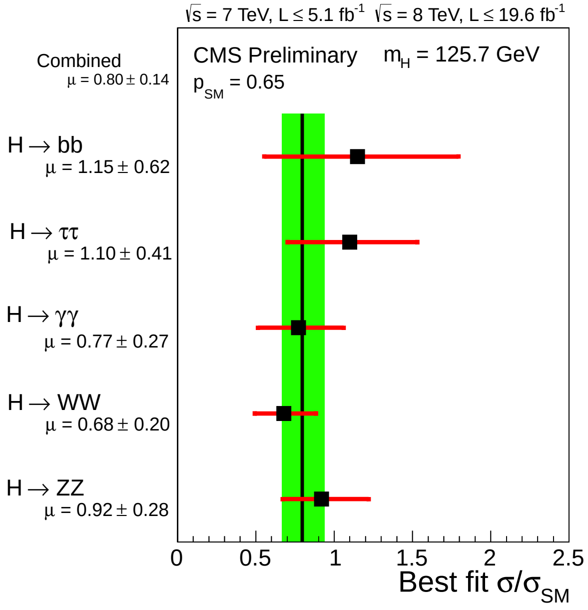
agreement at 20–30% level!

$\mu^{\rm ATL}_{\rm tot} = 1.30 \pm 0.30$

$\mu^{\rm CMS}_{\rm tot} = 0.87 \pm 0.23$

combined : $\mu_{\rm tot} \simeq 1$**!**





Higgs couplings to elementary particles as predicted by Higgs mechanism

- **couplings to WW,ZZ,$\gamma\gamma$ roughly as expected for a CP-even Higgs,**
- **couplings proportionial to masses as expected for the Higgs boson**

So, it is not only a “new particle”, the “126 GeV boson”, a “new state”...

IT IS A HIGGS BOSON!

But is it THE SM Higgs boson or A Higgs boson from some extension?

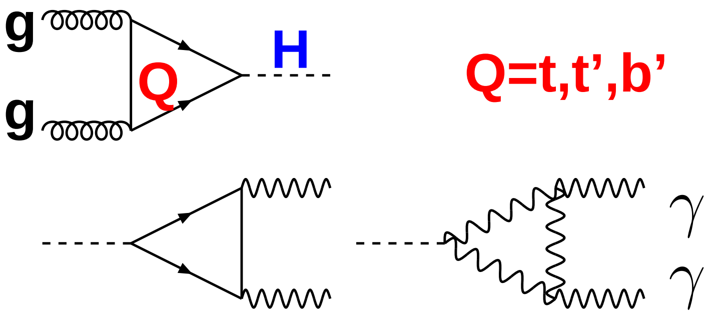
For the moment, it looks SM-like... Standardissimo (theory of everything)?

6. Implications of the discovery

Particle spectrum looks complete: no room for 4th fermion generation!

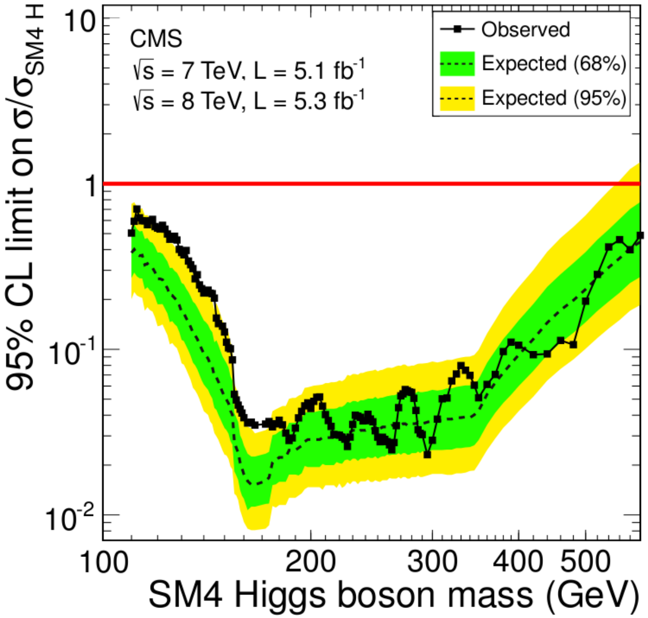
Indeed, an extra doublet of quarks and leptons (with heavy ν') would:

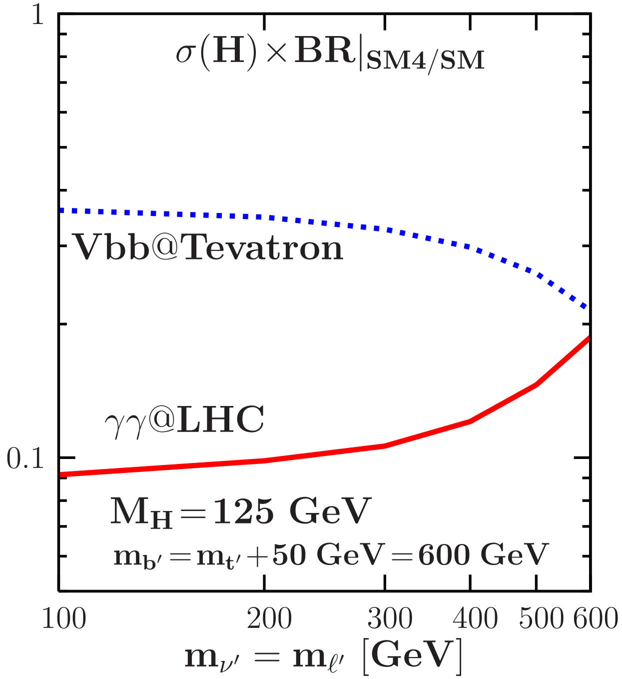
- **increase $\sigma(\mathrm{gg} \to \mathrm{H})$ by factor ≈ 9**
- **H$\to$gg suppresses BR(bb,VV) by $\approx$2**
- **strongly suppresses $\mathrm{BR}(\mathrm{H} \to \gamma\gamma)$**



Q=t,t',b'

NLO $\mathcal{O}(\mathrm{G_F m_{F'}^2})$ effects very important:





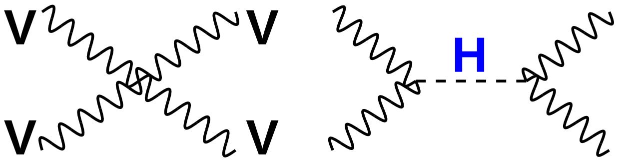
(Direct seach also constraining..) **Lenz....**

6. Implications of the discovery

- **For theory to preserve unitarity:**

we need Higgs with $M_H \lesssim 700$ GeV...

We have a Higgs and it is light: OK!



- **Extrapolable up to highest scales.**

$\lambda = 2M_H^2/v$ **evolves with energy**

– too high: non perturbativity

– too low: stability of the EW vaccum

$$\frac{\lambda(Q^2)}{\lambda(v^2)} \approx 1 + 3\frac{2M_W^4+M_Z^4-4m_t^4}{16\pi^2 v^4}\log\frac{Q^2}{v^2}$$

$$\lambda \geq @M_{Pl} \Rightarrow M_H \gtrsim 129\,\mathrm{GeV}!$$

at 2loops for $m_t^{pole} = 173$ GeV.....

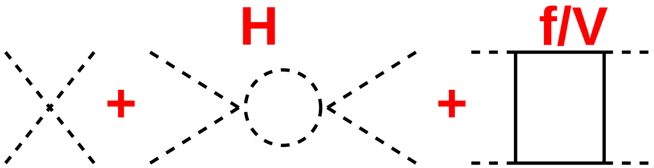
⇒ Degrassi et al., Bezrukov et al.

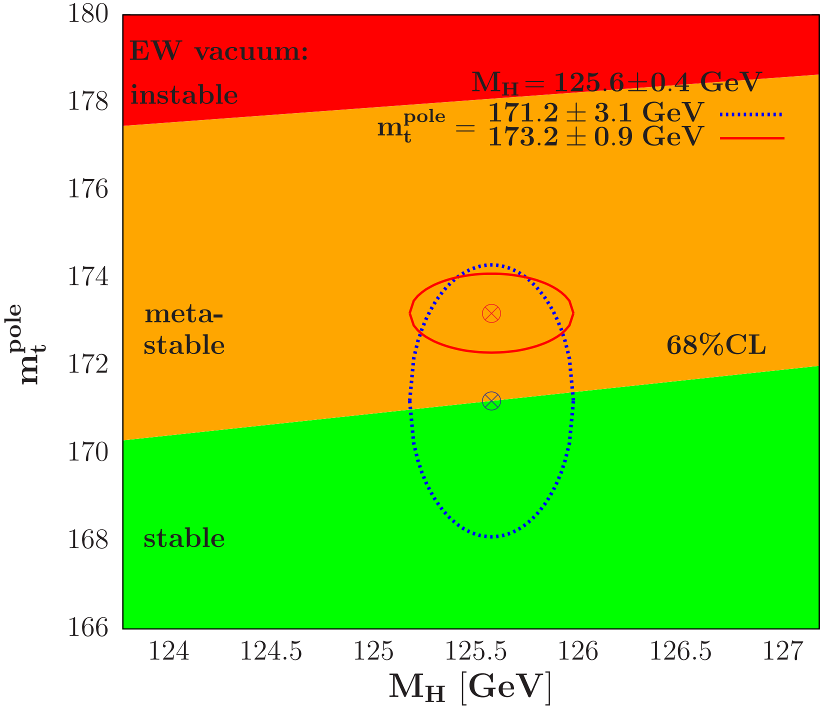
but what is measured m_t at TEV/LHC

$m_t^{pole} ? m_t^{MC} ?$ **not clear; much better:**

$m_t = 171 \pm 3$**GeV from** $\sigma(pp \to t\bar{t})$

issue needs further studies/checks...





Alekhin....

6. Implications of the discovery

Thus we have a theory for the strong+electroweak forces, the SM, that is:

- a relativistic quantum field theory based on a gauge symmetry,
- renormalisable, unitary and perturbative up to the Plankc scale,
- leads to a (meta)stable electroweak vaccum up to high scales,
- compatible with (almost) all precision data available to date...

Is it the theory of eveything and should we be satisfied with it? No:

The SM can only be a low energy manifestation of a more fundamental theory!

Indeed, the SM has the following problems which need to be cured:

- “Esthetical” problems with multiple and arbitrary parameters.
- “Experimental” problems as it does not explain all seen phenomena.
- ”A theory consistency” problem: the hierarchy/naturalness problem.

There must be beyond the Standard Model physics!