Higgs Physics
(in the SM and in the MSSM)

Abdelhak DJOUADI

(LPT CNRS & U. Paris-Sud)

- **The Higgs in the Standard Model**
- **Higgs decays**
- **Higgs production at hadron colliders**
- **Implications of the discovery for the SM**

- **The Higgs beyond the Standard Model**
- **The MSSM Higgs sector**
- **Implications of the discovery for the MSSM**
- **What next?**

1. The Higgs in the Standard Model

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

- $SU(2)_L \times U(1)_Y$ describes the electromagnetic+weak=EW 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: (μ, ν_μ, c, s) and (τ, ν_τ, t, b).

    There is no ν_R field (and neutrinos are thus exactly and stay massless).

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

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

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

Lagrangian simple: with fields strengths and covariant derivatives as QED

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

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

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

1. The Higgs in the Standard Model

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

$\frac{1}{2}M_V^2 V^\mu V_\mu$ **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) mass for instance 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 as e_L is in an SU(2) doublet while e_R is in an SU(2) singlet.

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

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

1. The Higgs in the Standard Model

Brout-Englert-Higgs: spontaneous electroweak symmetry breaking $\Rightarrow$
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 $SU(2)_L \times U(1)_Y$

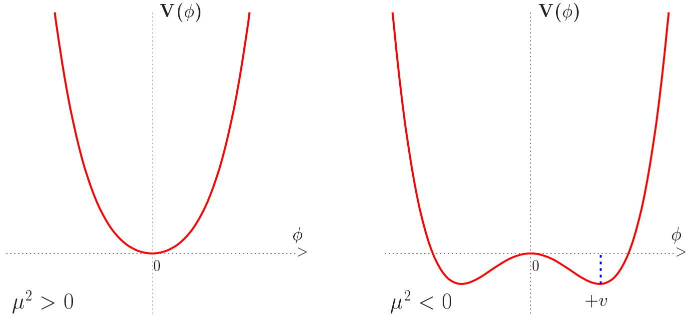
$$\mathcal{L}_S = (D^\mu \Phi)^\dagger (D_\mu \Phi) - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

$\mu^2 > 0$: 4 scalar particles..
$\mu^2 < 0$: Φ develops a vev:

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

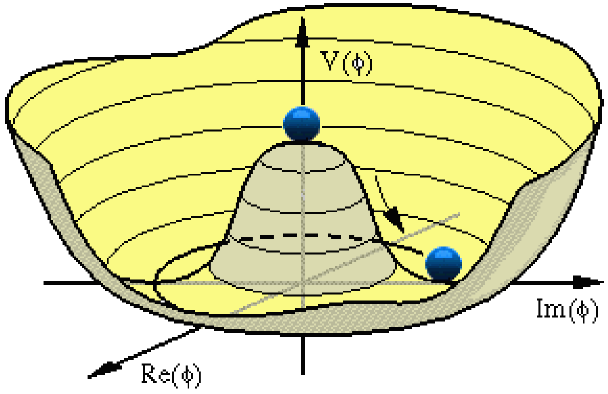
$$\text{with} \equiv v = (-\mu^2/\lambda)^{\frac{1}{2}}$$

$$= 246 \text{ GeV}$$



- **symmetric minimum: unstable**
- **true vacuum: degenerate**

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



1. The Higgs in the Standard Model

- **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]:**

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

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

1. The Higgs in the Standard Model

- **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^+, W_L^-, 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: $v = 1/(\sqrt{2} G_F)^{1/2} \sim 246$ GeV.

⇒ the photon stays massless and $U(1)_{QED}$ is preserved as it should.

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

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

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

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

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

What about the residual degree of freedom?

1. The Higgs in the Standard Model

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:

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

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

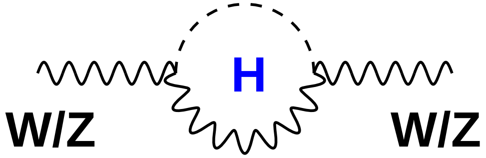
Since v is known, the only free parameter in the SM is M_H or λ.

1. The Higgs in the Standard Model

Constraints on $\mathrm{M_H}$ from pre–LHC experiments: LEP, Tevatron...

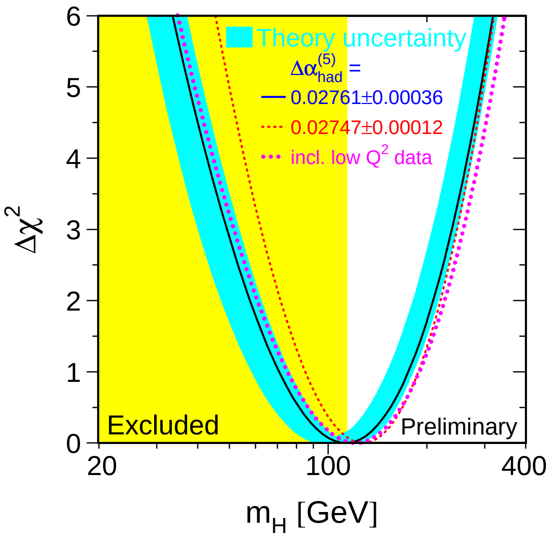
Indirect Higgs boson searches:

H contributes to RC to W/Z masses:



Fit the EW precision measurements:

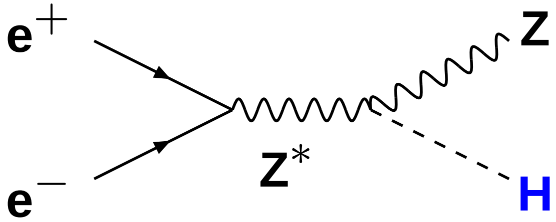
we obtain $\mathrm{M_H} = 92^{+34}_{-26}$ GeV, or



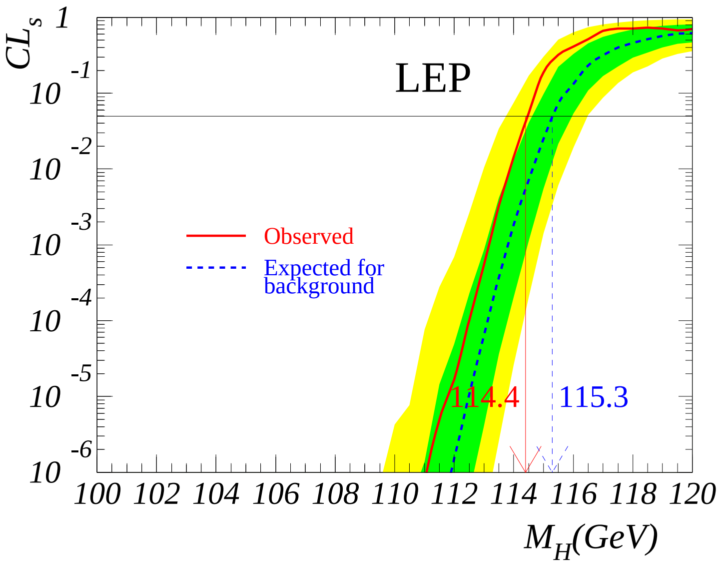
$\mathrm{M_H} \lesssim 160$ GeV at 95% CL

Direct searches at colliders:

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



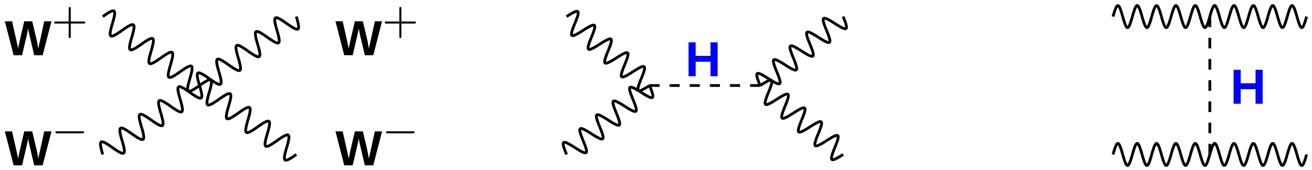
$\mathrm{M_H} > 114.4$ GeV @95%CL



Tevatron $\mathrm{M_H} \neq 160-175$ GeV

1. The Higgs in the Standard Model

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

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

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

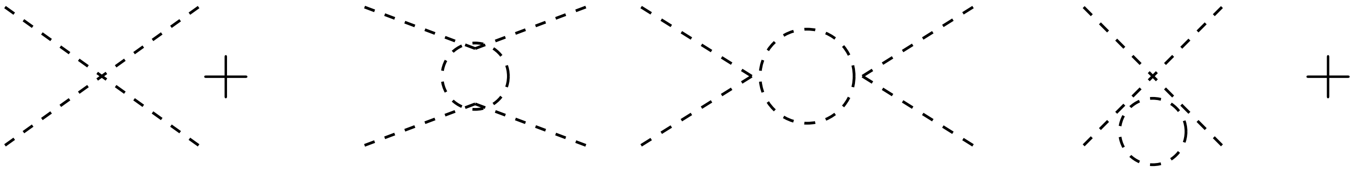
$$\text{unitarity} \Rightarrow \sqrt{s} \lesssim 1.7\ \text{TeV}\ \ (\sqrt{s} \lesssim 1.2\ \text{TeV})$$

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

1. The Higgs in the Standard Model

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

If the Higgs is very heavy: the H contributions to λ are 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 coupling λ becomes infinite:

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

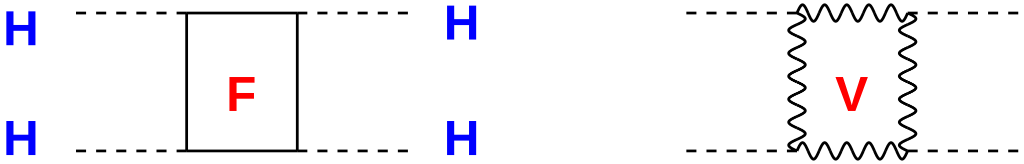
(comparable to results obtained with simulations on the lattice!)

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

(SM extrapolated up to ultimate scales, the GUT/Planck scales!).

1. The Higgs in the Standard Model

The top quark and gauge bosons also contribute to the evolution of λ: the contributions dominate over that of the H itself at low M_H values.



The RGE evolution of the coupling at one–loop order 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 (i.e. H is light), top loops might lead to $\lambda(0) < \lambda(v)$:

v is not the minimum of the potentiel and EW vacuum is unstable

$\Rightarrow$ 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

(a good reason why we have not observed the Higgs before LEP2...)

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

1. The Higgs in the Standard Model

Combine the two constraints and include all possible effects:

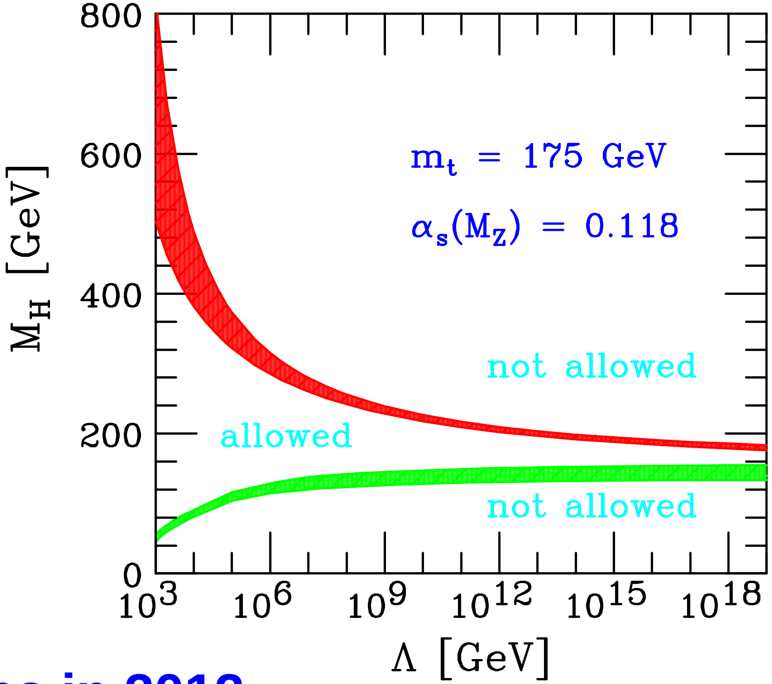
- dominant corrections at two loops,
- theoretical and experimental errors
- all possible refinements $\cdots$

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

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

Cabibbo, Maiani, Parisi, Petronzio

Hambye, Riesselmann



More up-to date (full two-loop) calculations in 2012:

Degrassi et al. and Berzukov et al.

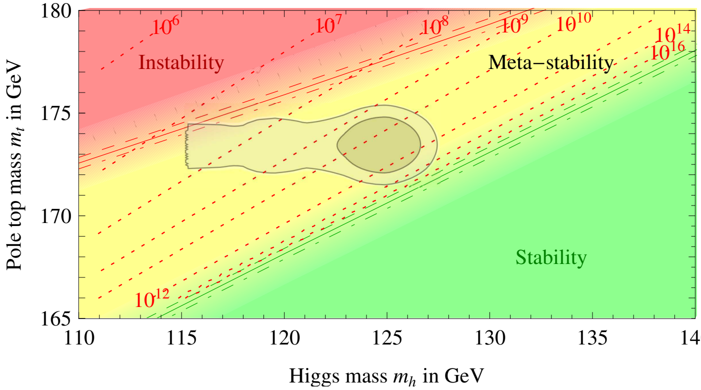
At two–loop for m_t^{pole}=173.1 GeV:

fully stable vacuum $M_H \gtrsim 129$ GeV,

but vacuum metastable below that!

metastability of vacuum is still OK:

unstable but long lived $\tau_{tunel} \gtrsim \tau_{univ}$!

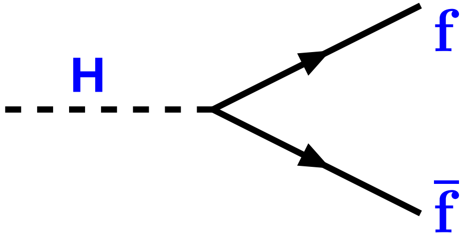


2. Higgs decays

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:



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

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

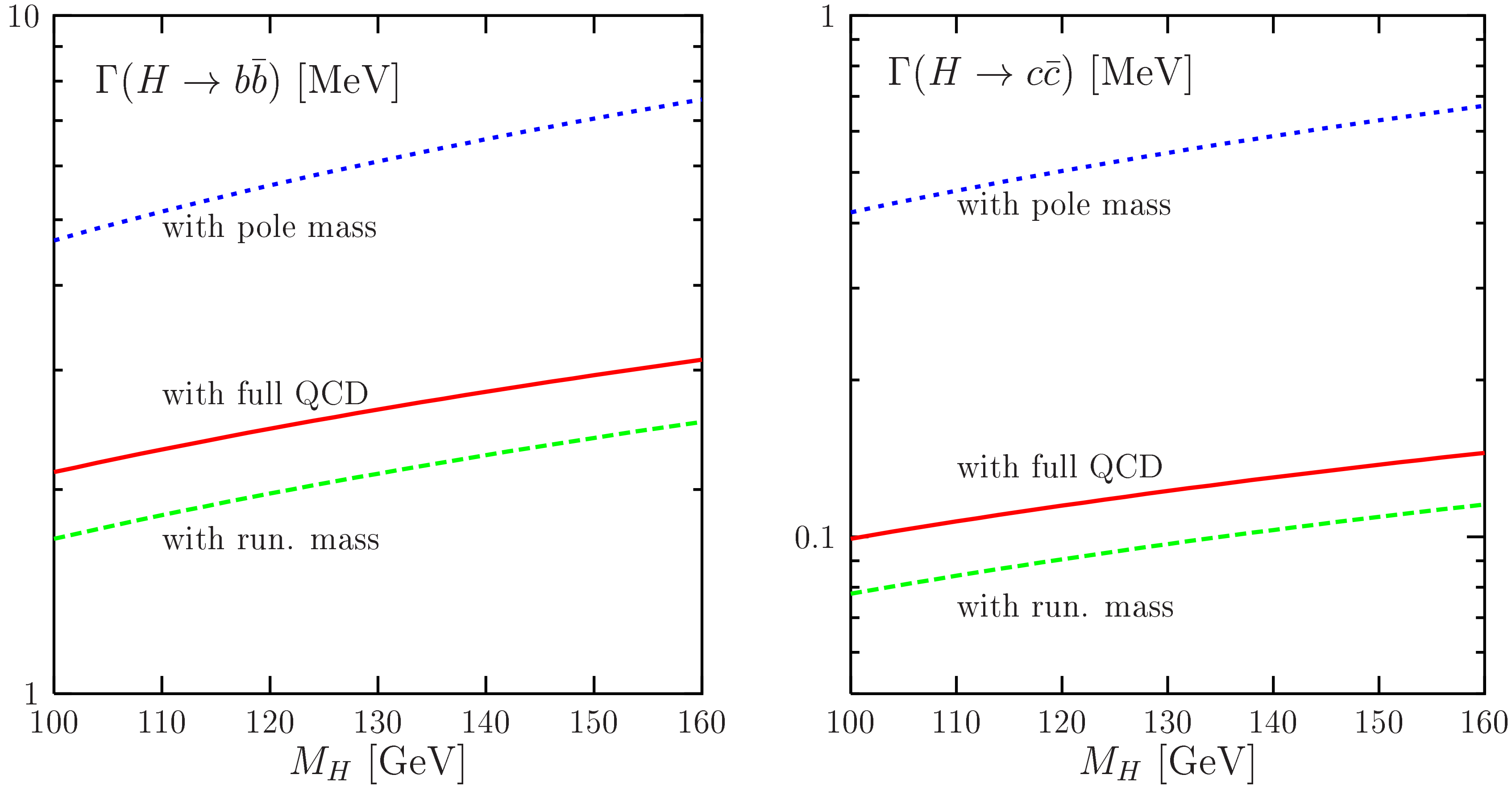
$$\mathrm{N_c} = \text{color number}$$

- **Only $\mathrm{b\bar{b}}, \mathrm{c\bar{c}}, \tau^+\tau^-, \mu^+\mu^-$ for $\mathrm{M_H} \lesssim 350$ GeV, also $\mathrm{H} \to \mathrm{t\bar{t}}$ beyond.**
- **$\Gamma \propto \beta^3$: H is CP–even scalar particle ($\propto \beta$ for pseudoscalar Higgs).**
- **Decay width grows as $\mathrm{M_H}$: moderate growth with the 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).**

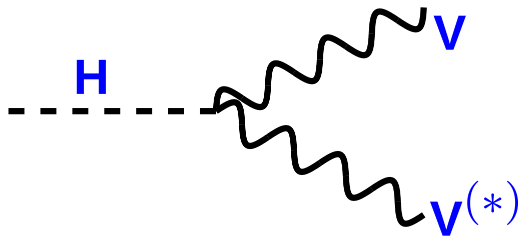
2. Higgs decays: fermions



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

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

2. Higgs decays: massive gauge bosons



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

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

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

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

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

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

2. Higgs decays: massive gauge bosons

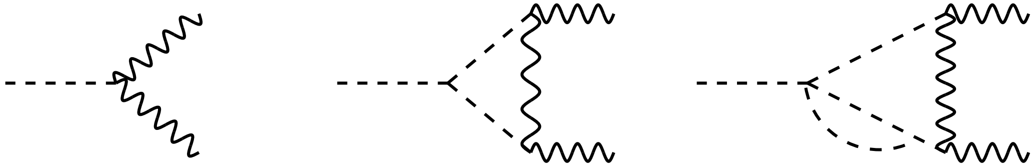
Electroweak radiative corrections to $H \to VV$:

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

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

$H \to WW$: 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:



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

$M_H \sim \mathcal{O}(10\ \text{TeV}) \Rightarrow$ 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:

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

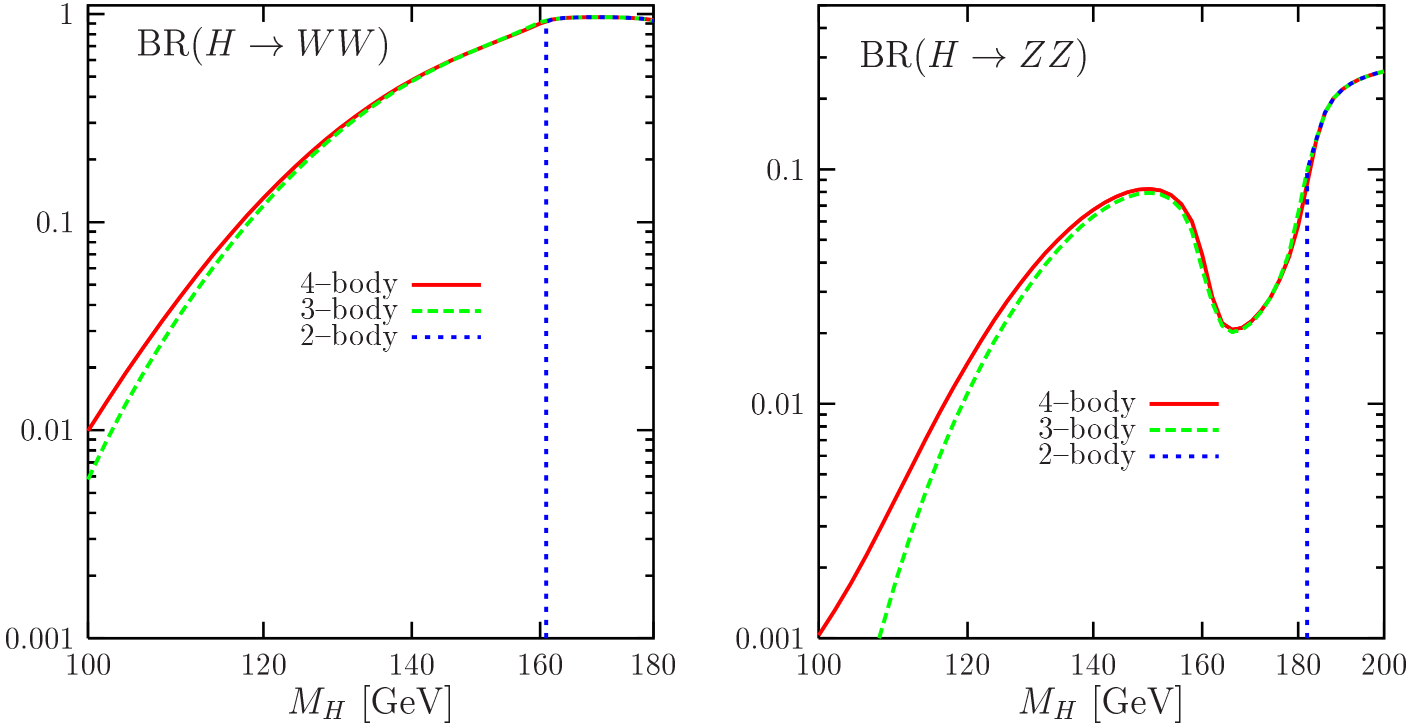
2. Higgs decays: massive gauge bosons

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

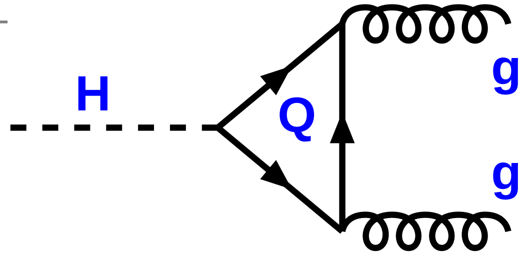
$$\Gamma(\mathrm{H} \to \mathrm{V}^*\mathrm{V}^*) = \frac{1}{\pi^2} \int_0^{M_H^2} \frac{dq_1^2 M_V \Gamma_V}{(q_1^2 - M_V^2)^2 + M_V^2 \Gamma_V^2} \int_0^{(M_H - q_1)^2} \frac{dq_2^2 M_V \Gamma_V}{(q_2^2 - M_V^2)^2 + M_V^2 \Gamma_V^2} \Gamma_0$$

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

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



2. Higgs decays: gluons



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

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

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

- 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.

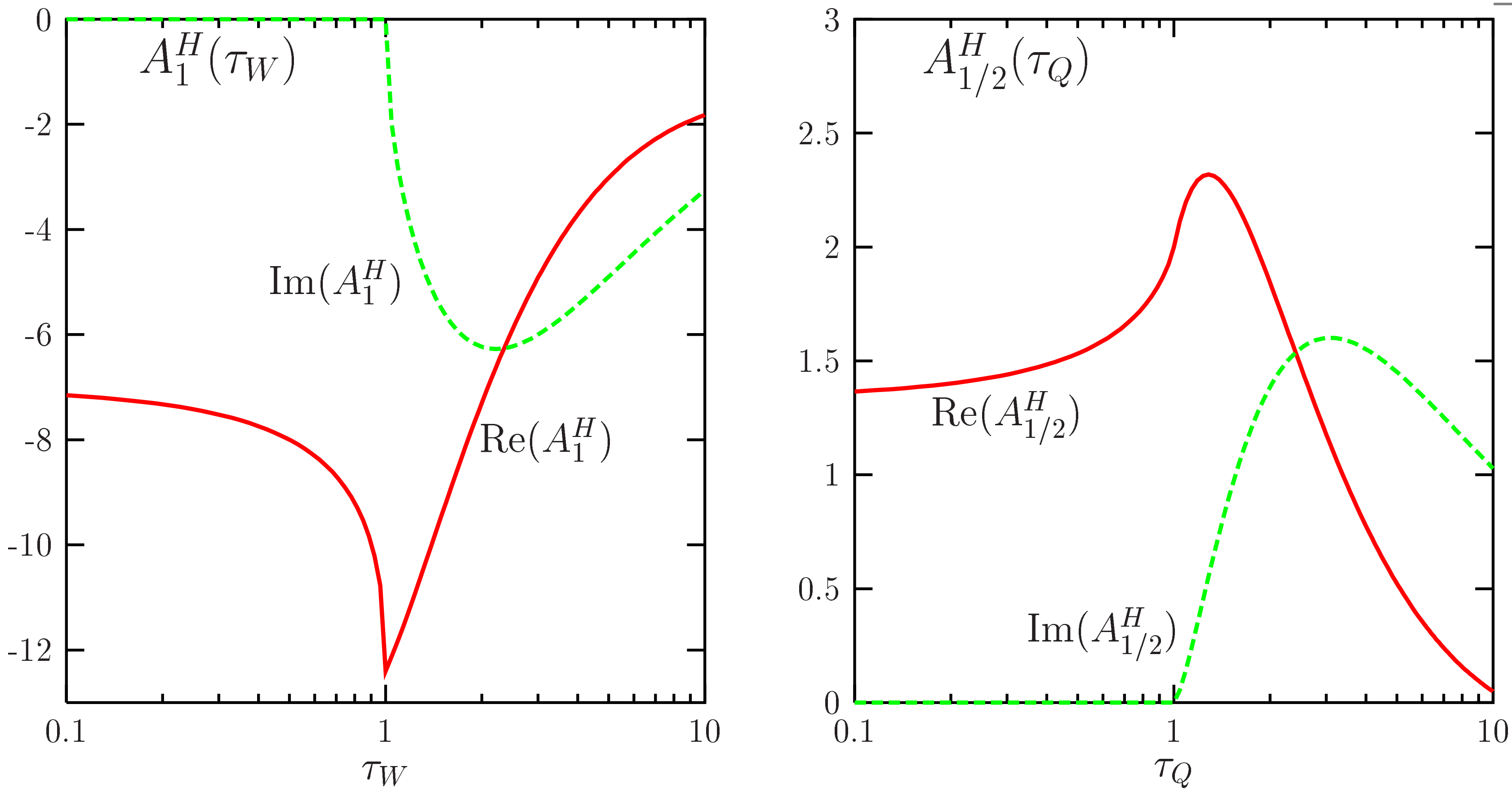
Good approximation in decay: include only t–loop with $m_Q \to \infty$.

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

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

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

2. Higgs decays: gluons



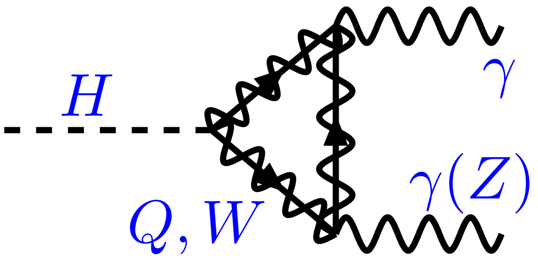
W and fermion amplitudes in $\mathbf{H \to \gamma\gamma}$ as function of $\mathbf{\tau_i = M_H^2/4M_i^2}$.

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

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

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

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

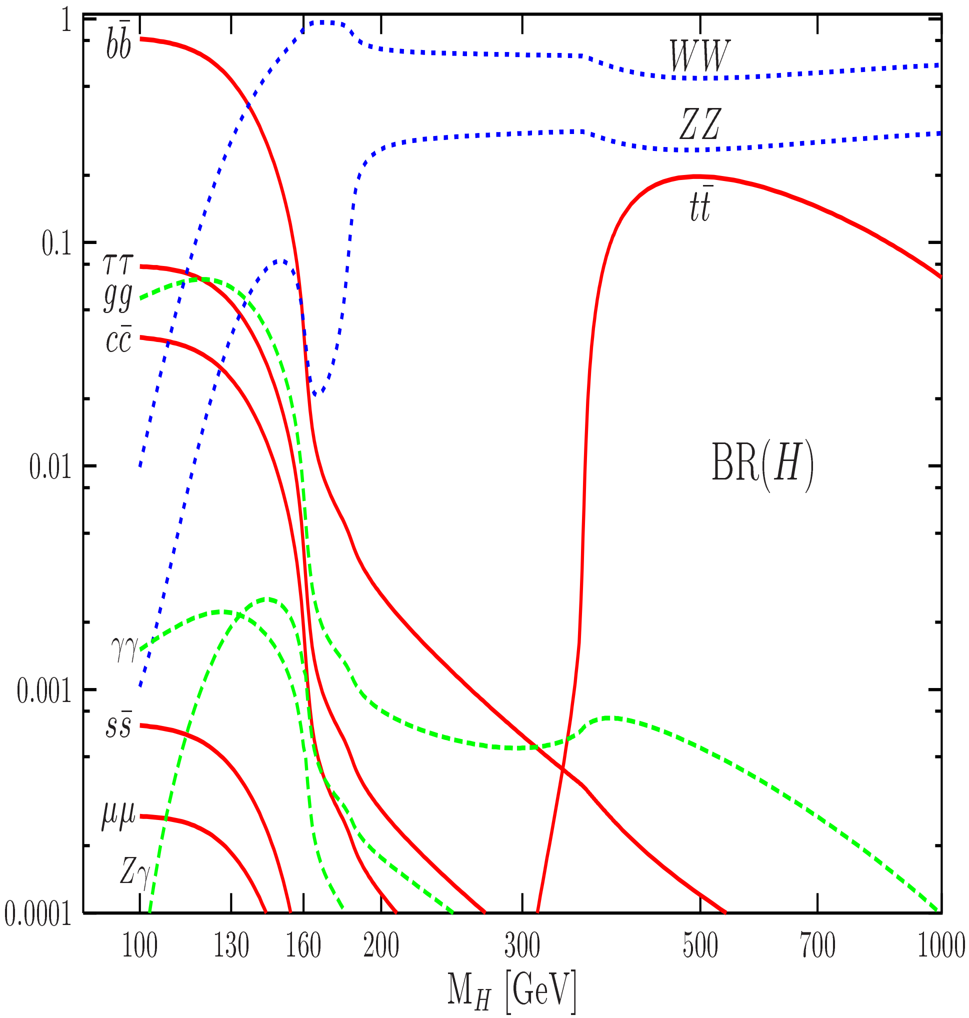
2. Higgs decays: branching ratios

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

- **'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:**
- – $\mathrm{H} \to \mathbf{WW^*}, \mathbf{ZZ^*}$ **up to** $\gtrsim 2\mathrm{M_W}$
- – $\mathrm{H} \to \mathbf{WW}, \mathbf{ZZ}$ **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)

2. Higgs decays: total width

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

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

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

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

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

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

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

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

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

- **Total Higgs decay width:**

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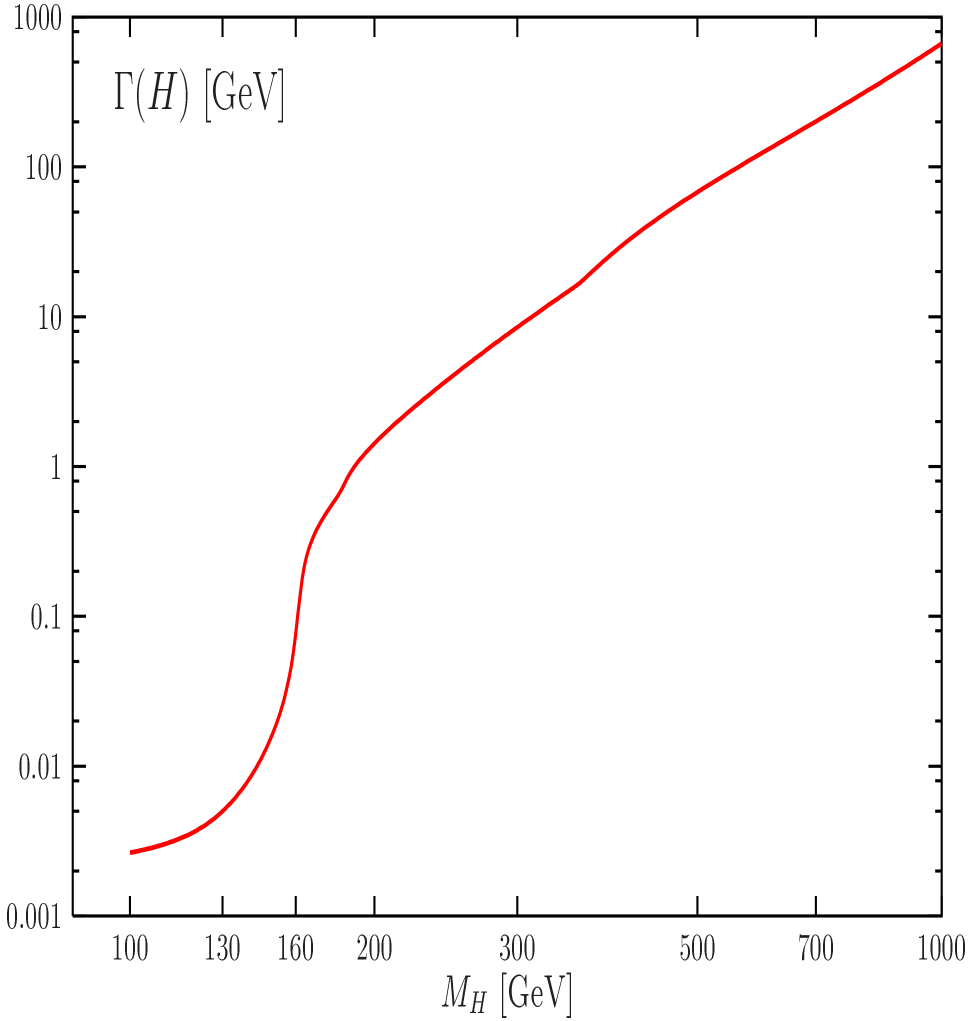
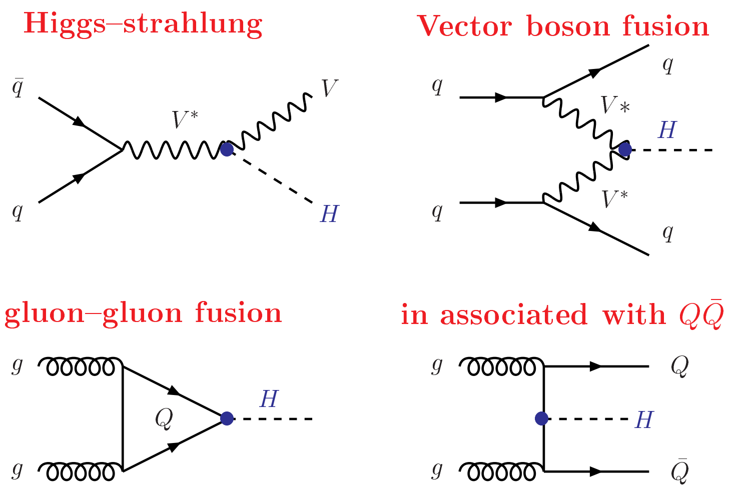
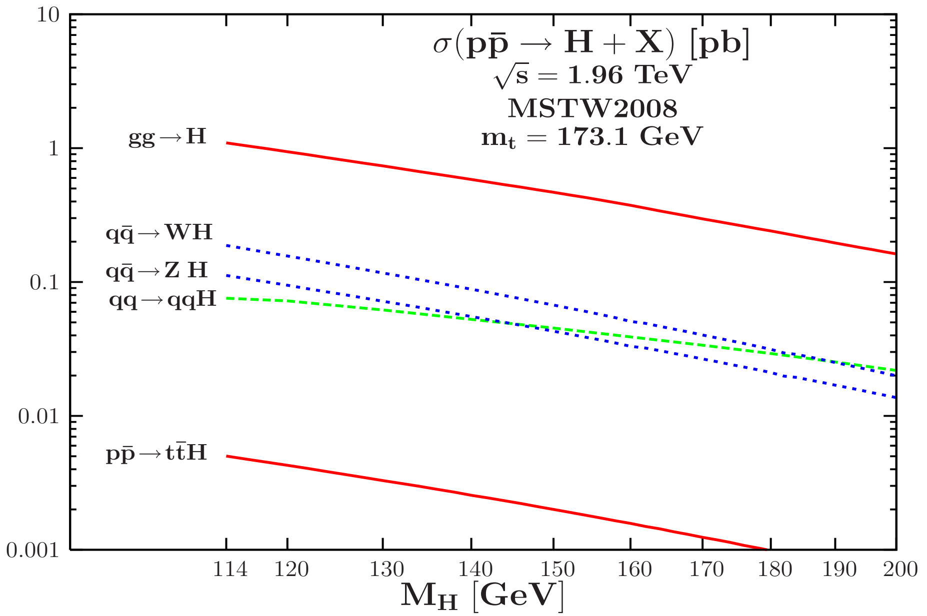


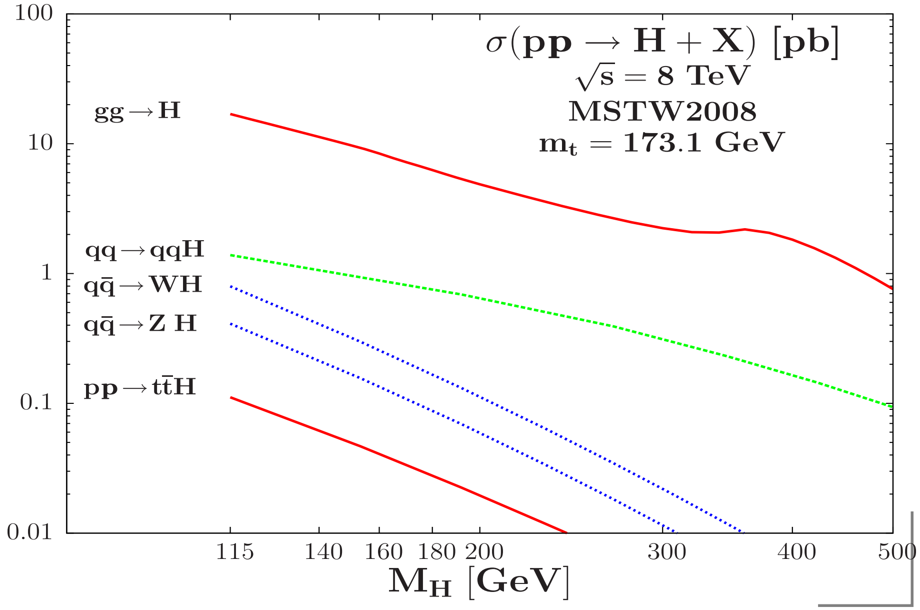
HDECAY (AD, Spira, Kalinowski, 97-14)

3. Higgs production at LHC

Main Higgs production channels







Large production cross sections

with gg$\to$ H by far dominant process

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

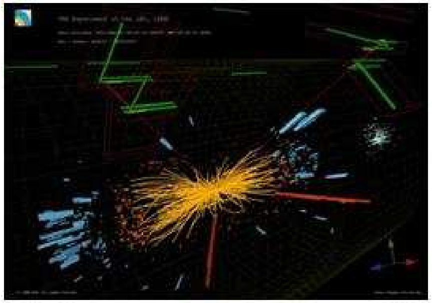
$\Rightarrow \mathcal{O}(10^3)$ events @Tevatron

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

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

3. Higgs production at LHC: premices

$\Rightarrow$ 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...)

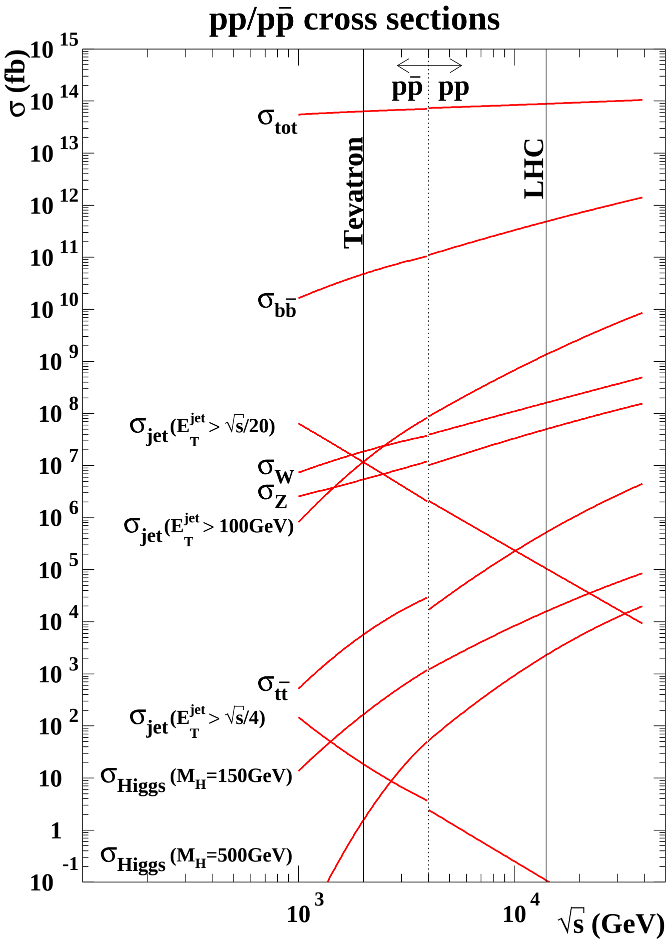
- Have a precise knowledge of S and B rates

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

- Gigantic experimental + theoretical efforts

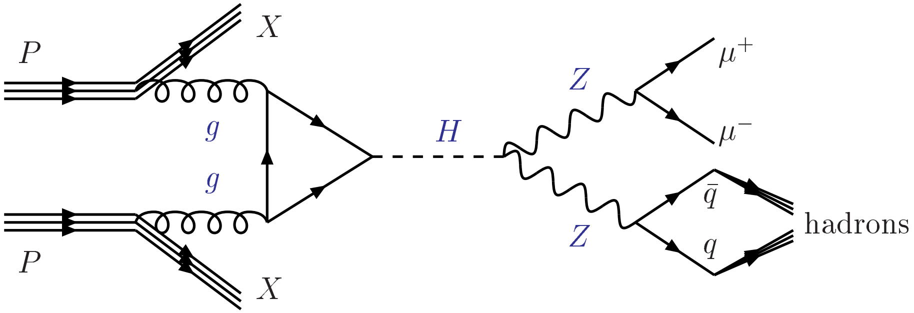
(more than 30 years of very hard work!)

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



3. Higgs production at LHC: premices

Best 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: the two can factorise in production at a scale μ_F.

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

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

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

Convolute with gluon densities to obtain total hadronic cross section

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

3. 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 $\alpha_{\bf s}^{\bf n} \log^{\bf m}({\bf Q}/{\bf M_H})$ where Q is either large or small...

- **Since α_s is large, these corrections are in general very important,**

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

- **Choose a (natural scale) which absorbs/resums the large logs,**

⇒ higher orders provide stability against $\mu_{\bf R}/\mu_{\bf F}$ 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.

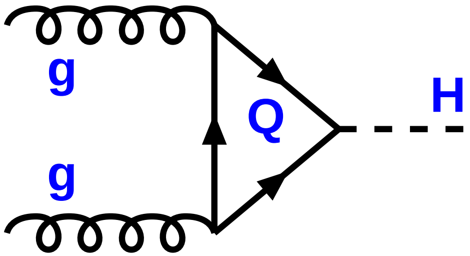
- **Also, precise knowledge of σ is not enough: need to calculate some kinematical distributions (e.g. ${\bf p_T}, \eta, \frac{{\rm d}\sigma}{\rm dM}$) to distinguish S from B.**
- **In fact, one has to do this for both the signal and background (unless directly measurable from data): the important quantity is ${\bf s} = {\bf N_S}/\sqrt{\bf N_B}$.**

⇒ a lot of theoretical work is needed!

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

3. Higgs production at LHC: gg fusion

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



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

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

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.

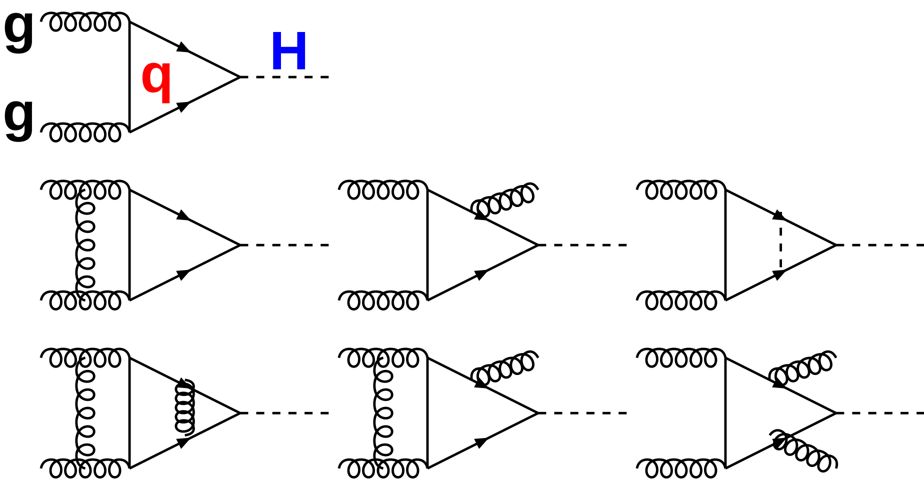
- Very large QCD RC: the two– and three–loops have to be included.
- Also the Higgs P_T is zero at LO, must generated at NLO.

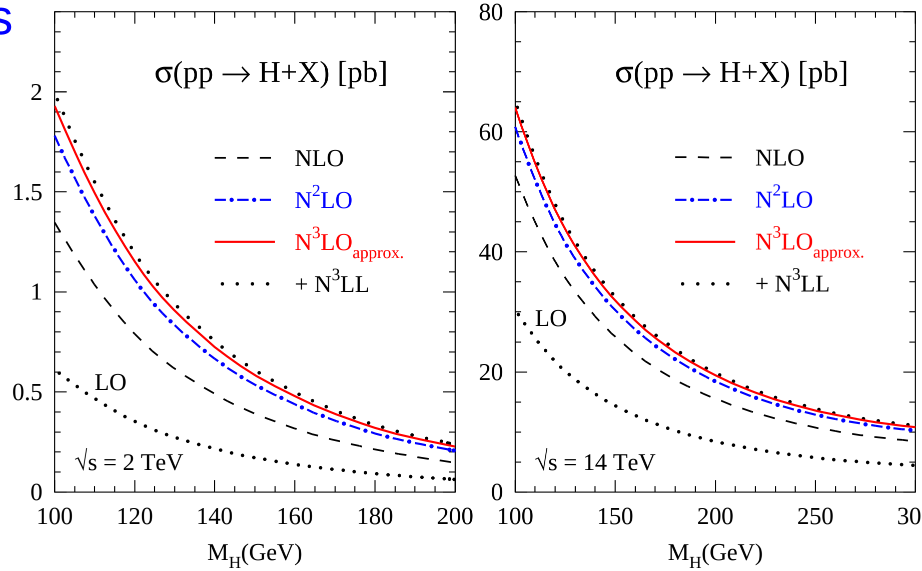
3. Higgs production at LHC: gg fusion

LO[a]: already at one loop
QCD: exact NLO[b] : $K \approx 2$ (1.7)
EFT NLO[c]: good approx.
EFT NNLO[d]: $K \approx 3$ (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 $\sigma^{\text{theory}}_{gg\to H}$ long story (70s–now) ...





Moch+Vogt

3. 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.

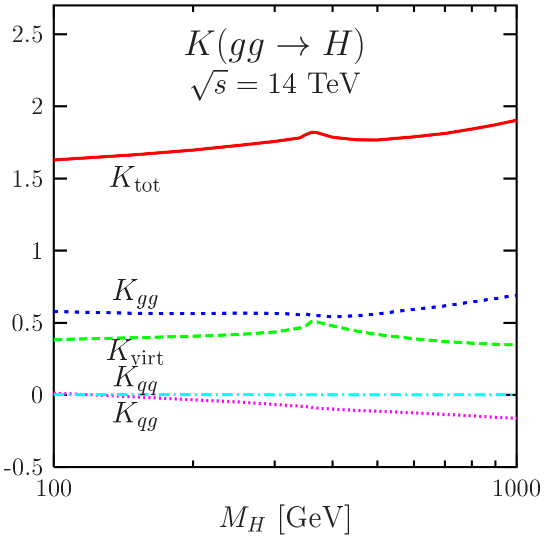
- **Corrections have been calculated in $\mathrm{m_t} \to \infty$ limit beyond NLO.**

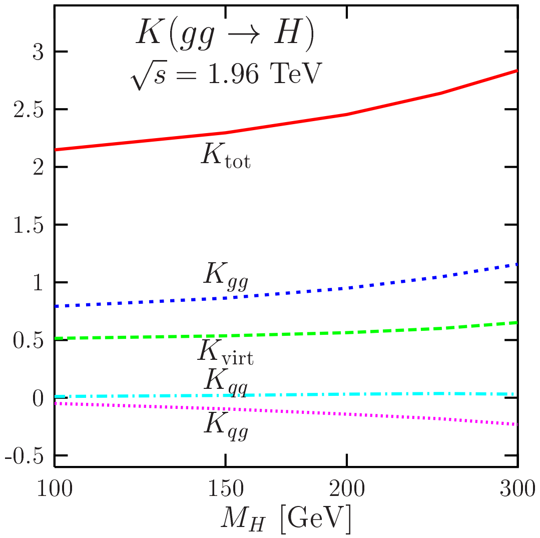
– moderate increase at NNLO by 30% and stabilisation with scales...

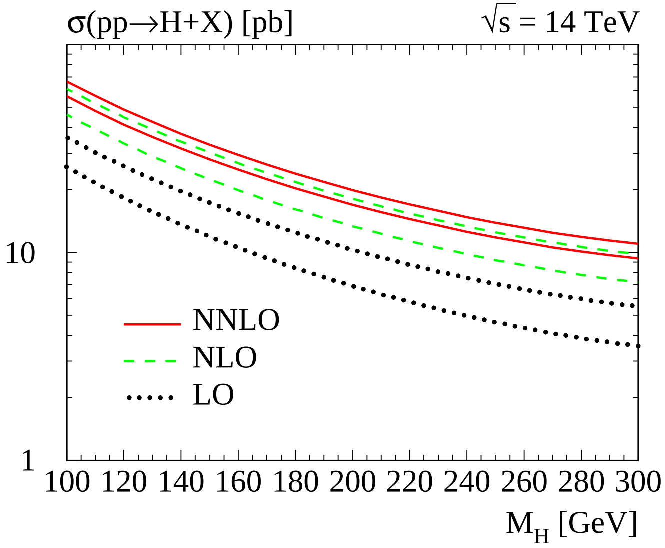
– soft–gluon resummation performed up to NNLL: $\approx$ 5–10% effects.

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.







3. Higgs production at LHC: gg fusion

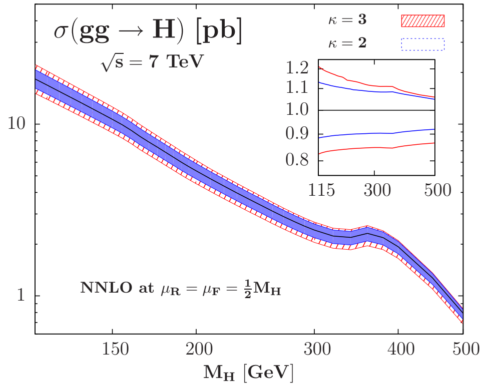
Despite of that, the $gg \to H$ cross section still affected by uncertainties

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

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

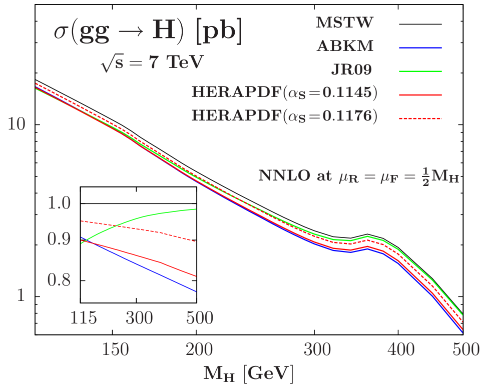
$$\mu_0/\kappa \leq \mu_R, \mu_F \leq \kappa\mu_0$$

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



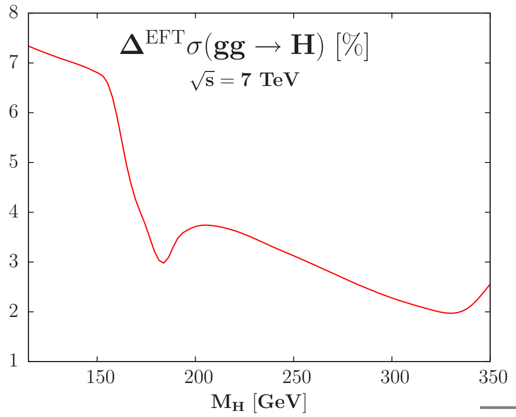
- **Uncertainty from EFT approach at NNLO**

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

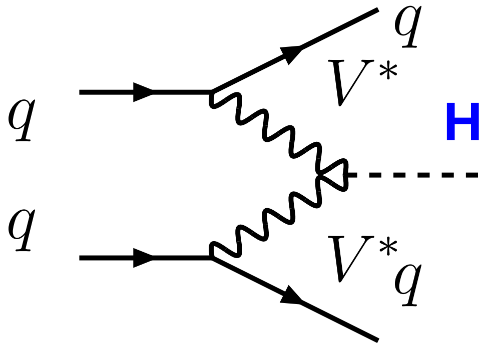
- **Include ΔBR($H \to X$) of at most few %**

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

LHC-HxsWG; Baglio+AD $\Rightarrow$



3. Higgs production at LHC: VV fusion



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

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

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

$\Rightarrow$ most important process at the LHC after $\rm gg \to H$.

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!

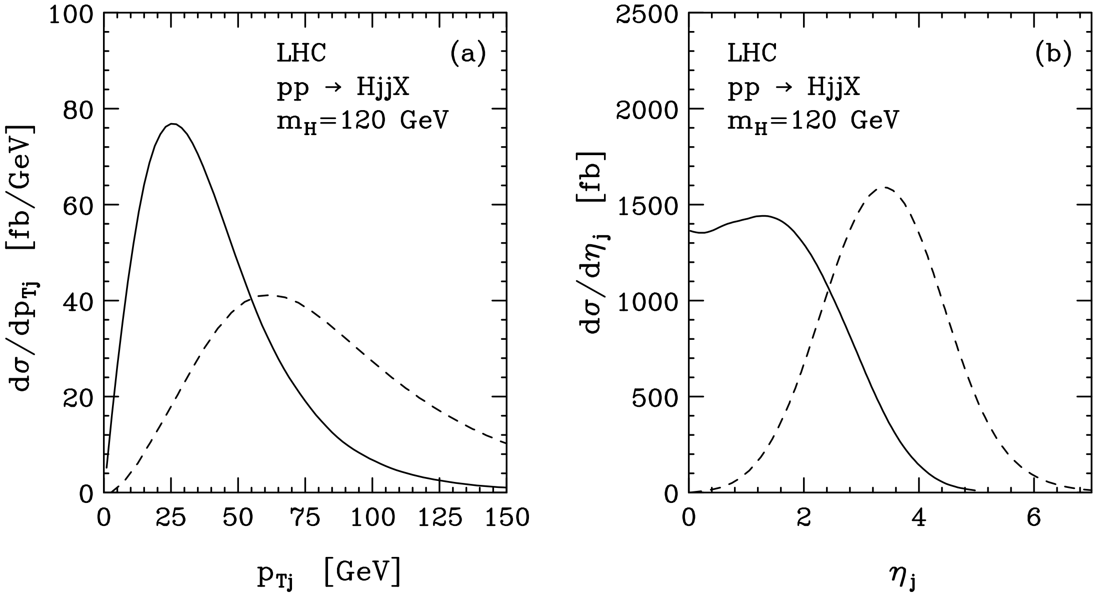
– NNLO corrections recently calculated in this scheme: very small.
– EW corrections are also small, of order of a few %.

3. 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 $\mathrm{P_T}$ 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).**

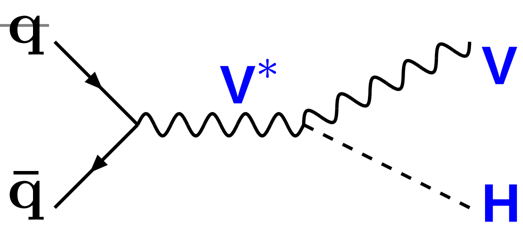
$\Rightarrow$ allows to suppress backgrounds to the level of H signal: $\mathrm{S/B} \sim 1$.



—– 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 $\mathrm{gg \to H+jj}$ process not so small...

3. 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 $q^2 \neq M_V^2$:

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

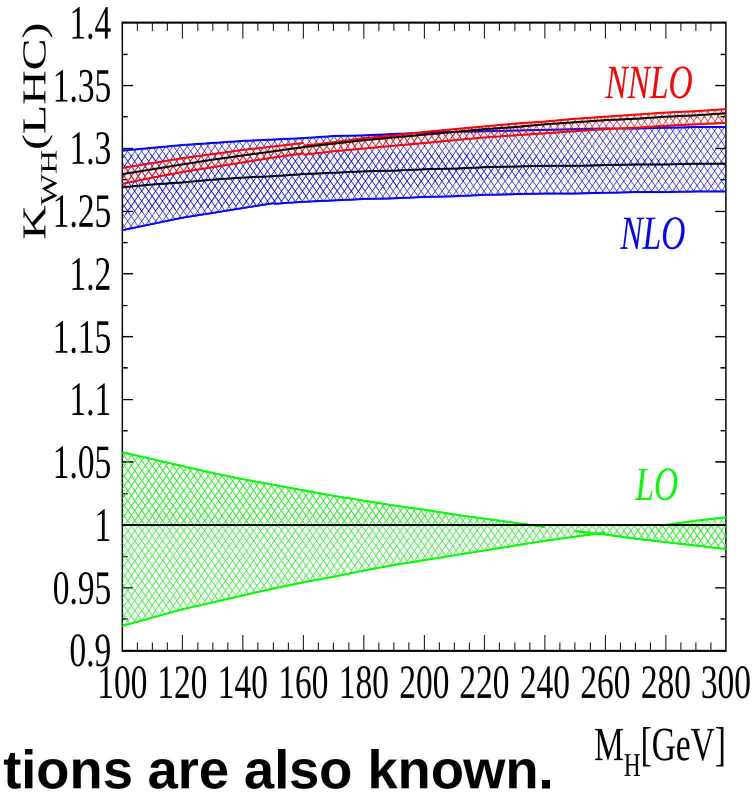
RC $\Rightarrow$ those of known DY process

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

QCD RC in HV known up to NNLO

(borrowed from Drell-Yan: K$\approx$ 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**

3. 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:

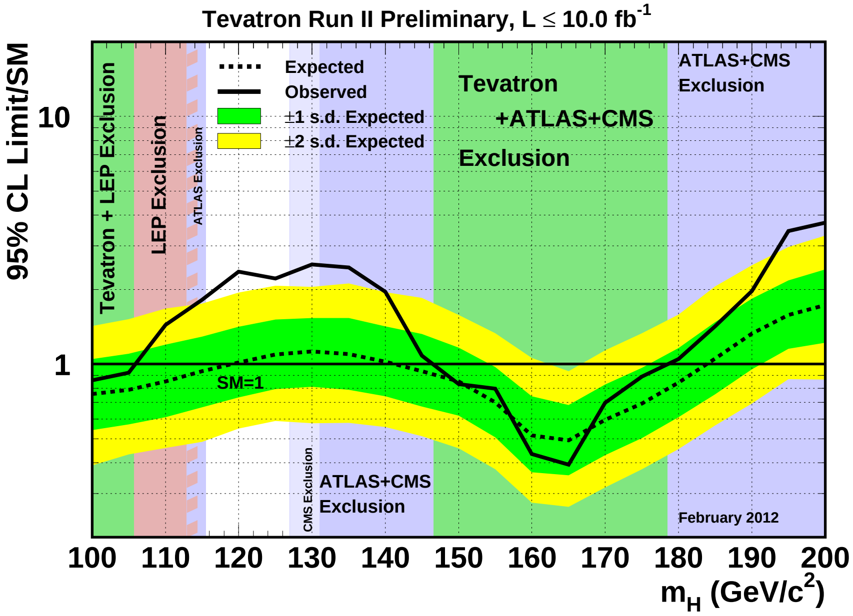
$\mathrm{M_H}\lesssim 130$ **GeV:** $\mathrm{H}\to\mathrm{b\bar{b}}$

$\Rightarrow \ell\nu\mathrm{b\bar{b}},\ \nu\bar{\nu}\mathrm{b\bar{b}},\ \ell^+\ell^-\mathrm{b\bar{b}}$

(help for $\mathrm{HZ}\to\mathrm{b\bar{b}}\ell\ell, \mathrm{b\bar{b}}\nu\nu$)

$\mathrm{M_H}\gtrsim 130$ **GeV:** $\mathrm{H}\to\mathrm{WW}^*$

$\Rightarrow\ \ell^\pm\ell^\pm\mathrm{jj},\ 3\ell^\pm$



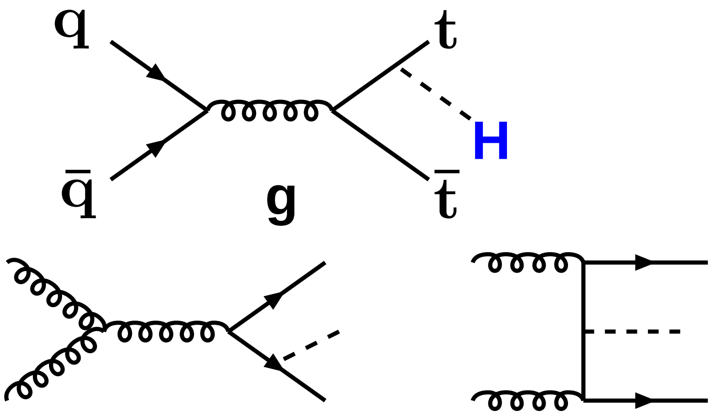
Sensitivity in the low H mass range: excludes low $\mathrm{M_H}\lesssim 110$ GeV values

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

3. Higgs production at LHC: Htt production

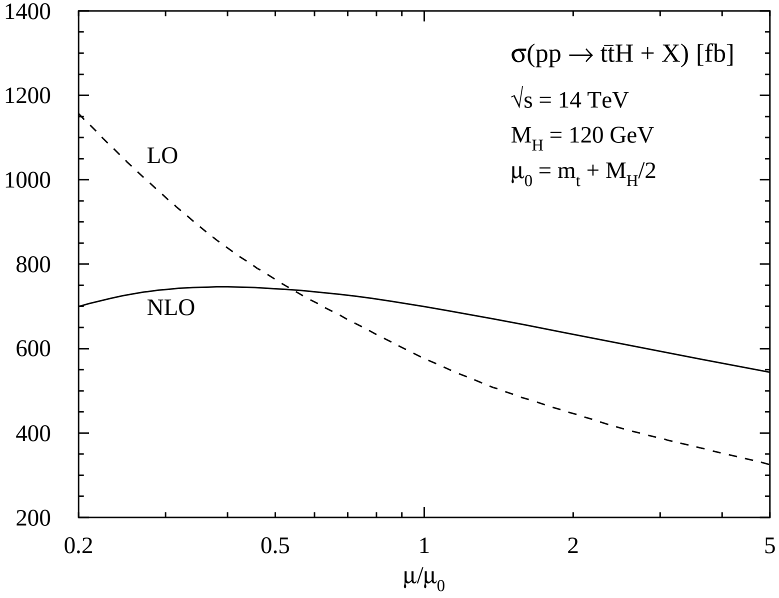
Most complicated process for Higgs production at hadron colliders:

– 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: $\mathrm{p_T^{top}, P_T^H}$), 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: $\mathrm{pp \to Htt \to \gamma\gamma + X, \nu\nu\ell^\pm\ell^\mp, b\bar{b}\ell^\pm}$.**
- **Possibility for a 5 signal at $\mathrm{M_H} \lesssim 140$ GeV at high luminosities.**

3. Higgs production at LHC: summary

Last expectations of ATLAS/CMS...)

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

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!!

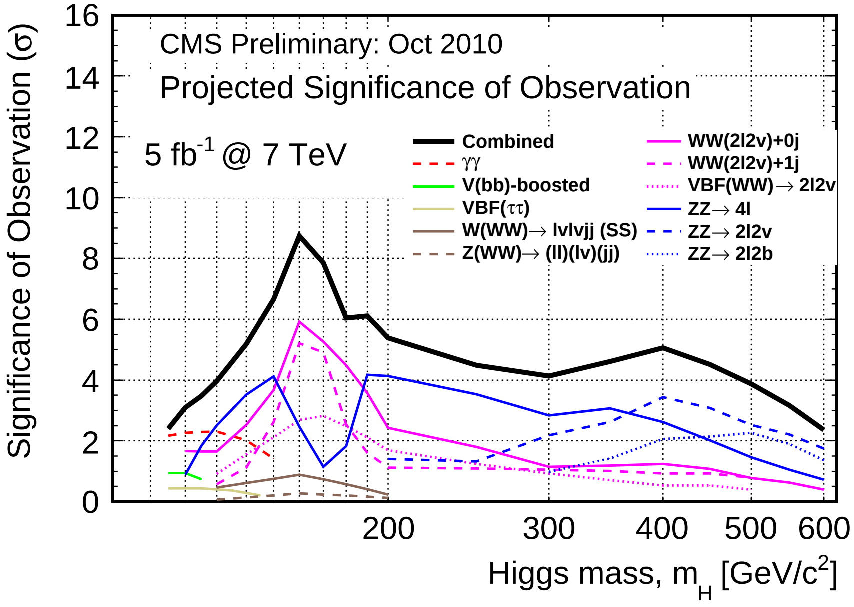
Full LHC: same as lHC plus some others

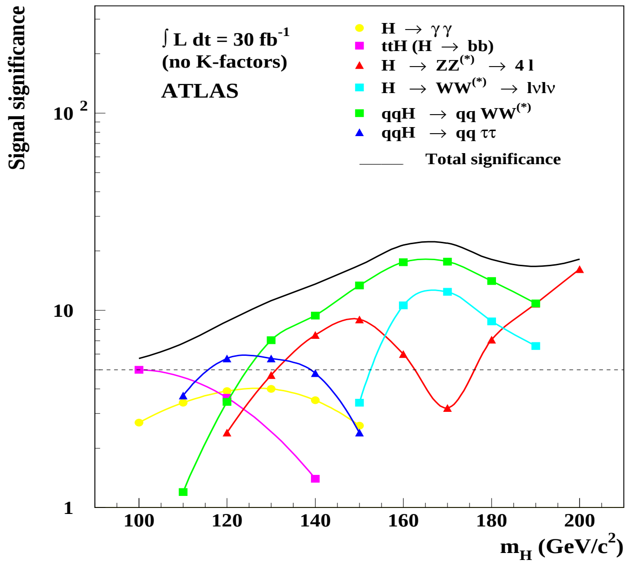
– VBF: $qqH\to\tau\tau,\gamma\gamma,ZZ^*,WW^*$

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

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

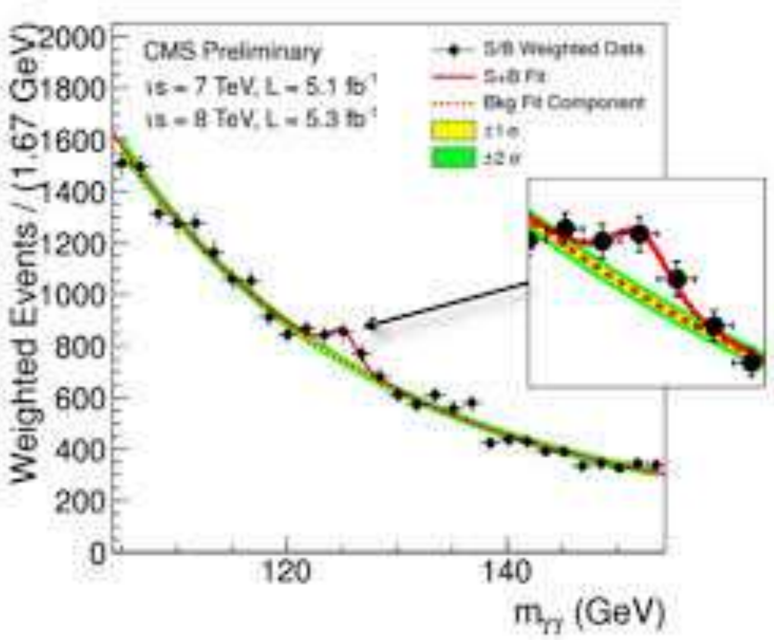
Conclusion? Mission accomplie!

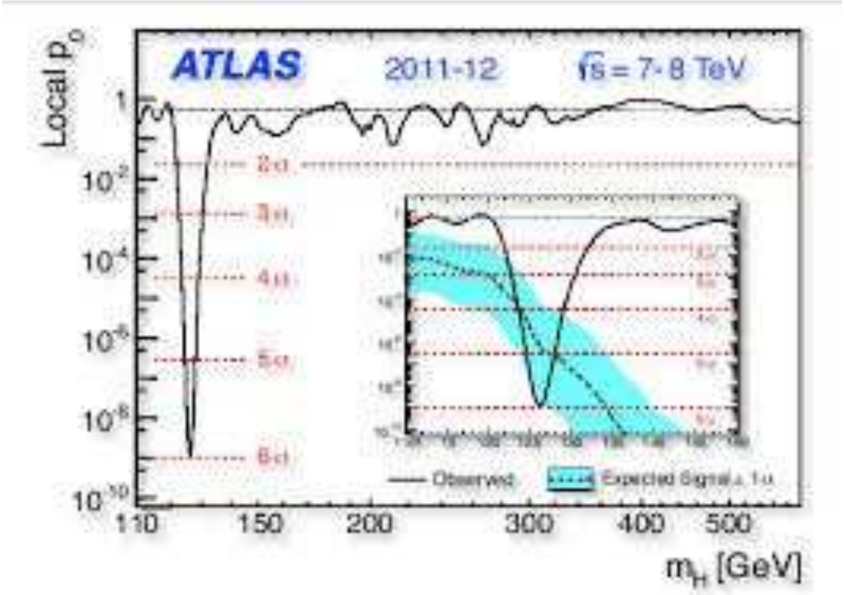




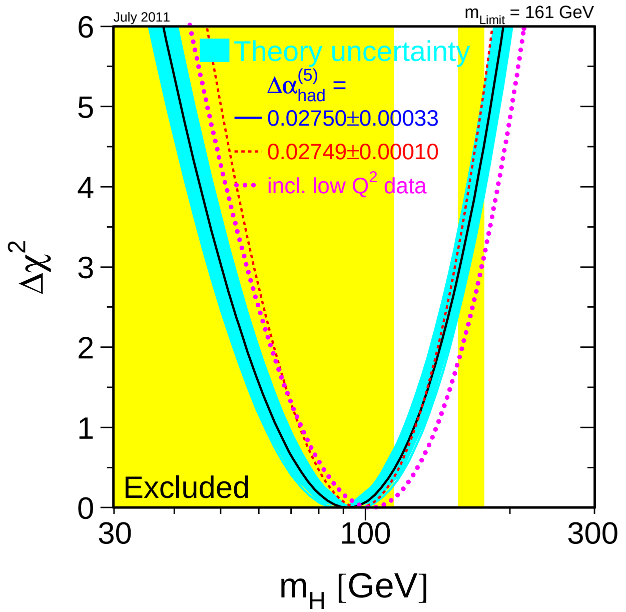
4. Implications of the discovery

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



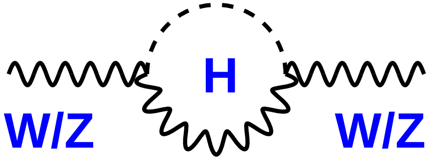


4. Implications of the discovery

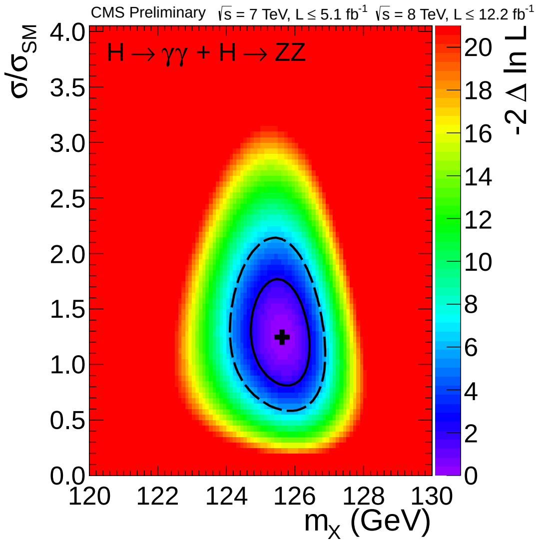


And the observed new state looks
as the long sought SM Higgs boson:
a triumph for high-energy physics!

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

$M_H \lesssim 160$ **GeV at 95% CL**

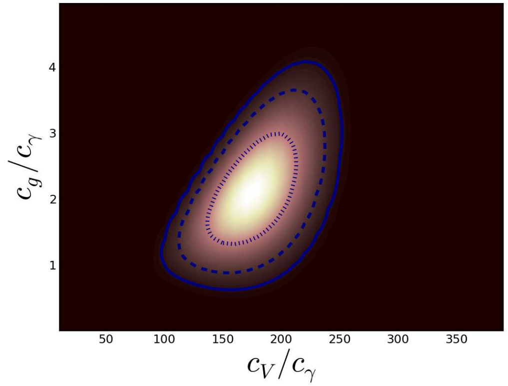
versus "observed" $M_H = 125$ GeV.

A very non–trivial check of the SM!

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

4. Implications of the discovery

But lets check it is indeed a Higgs!



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

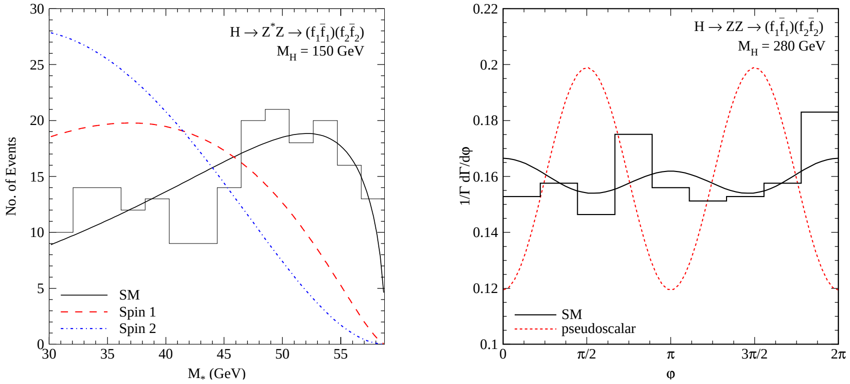
- not spin–1: Landau–Yang
- could be spin–2 like graviton? **Ellis et al.**

– miracle that couplings fit that of H,

– “prima facie” evidence against it:

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

many th. analyses (no suspense...)



CP no: even, odd, or mixture?

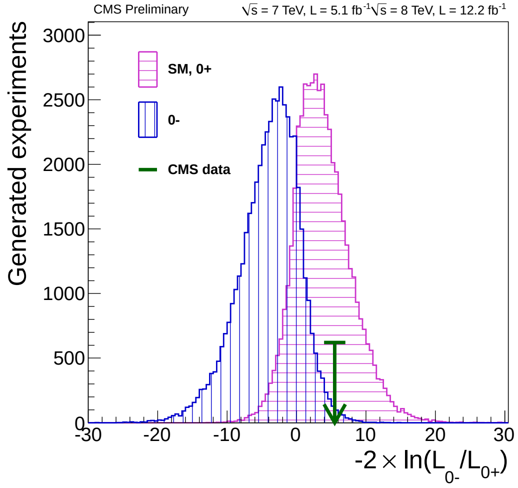
(more important; CPV in Higgs!)

ATLAS and CMS CP analyses for pure CP–even vs pure–CP–odd

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

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

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



4. 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 $\hat{\mu}_{\mathrm{VV}}$

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

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

gives upper bound on CP mixture:

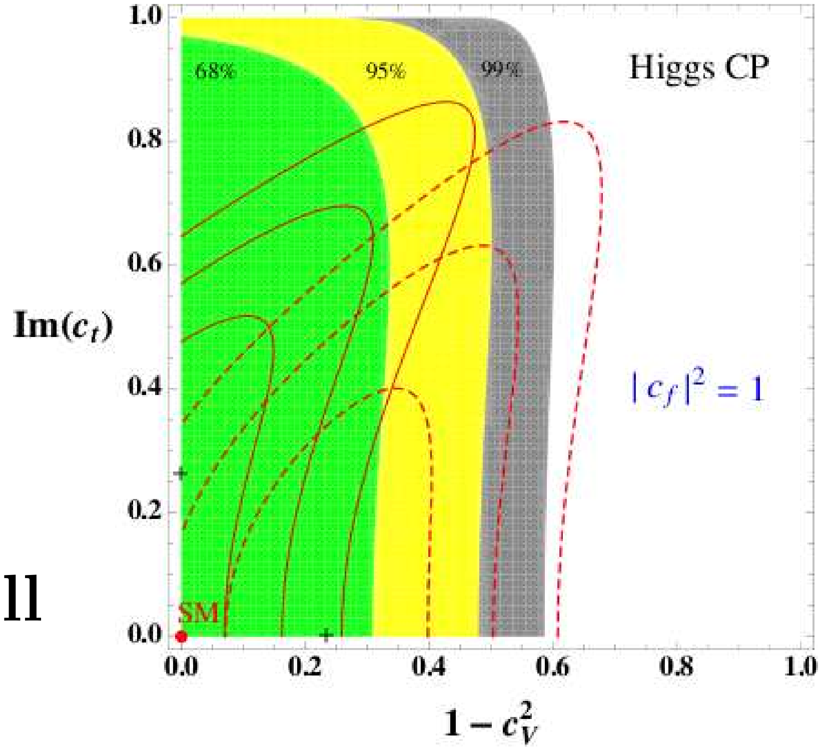
$\eta_{\mathrm{CP}} \equiv 1 - \mathrm{c_V^2} \gtrsim 0.5@68\%\mathrm{CL}$

Direct probe: $\mathrm{g_{Hff}}$ **more democratic**

$\Rightarrow$ **processes with fermion decays.**

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

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



Extremely challenging even at HL-LHC...

Moreau...

4. Implications of the discovery

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

Fit of all LHC Higgs data $\Rightarrow$

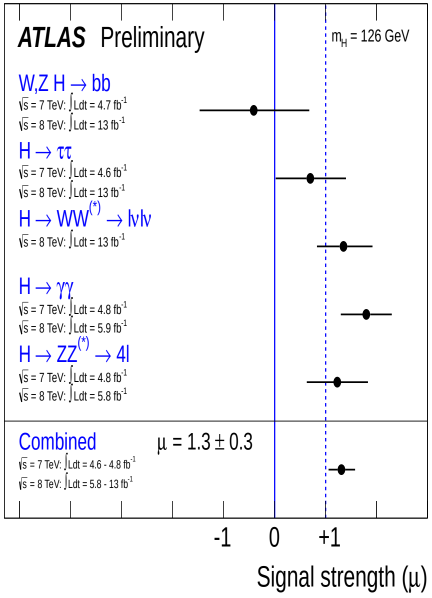
$\hat{\mu}^{\rm signal}_{\rm strength}$ =observed/SM:

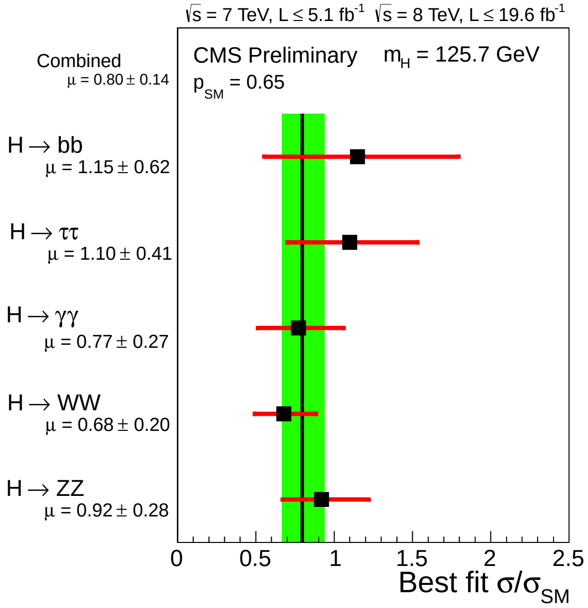
agreement at 20–30% level.

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

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

$$\text{combined} : \hat{\mu}_{\rm tot} \simeq 1!$$





Higgs couplings to elementary particles as predicted by BEH mechanism:

- couplings to WW,ZZ,$\gamma\gamma$ roughly as expected for a CP-even Higgs,
- couplings proportional 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?

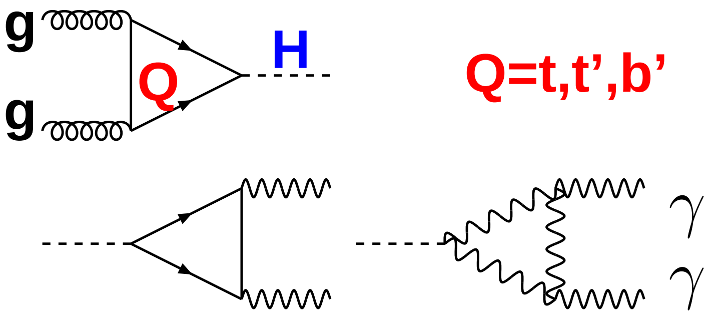
For the moment, it looks SM–like... Standardissimo (theory of everything)?

4. Implications of the discovery

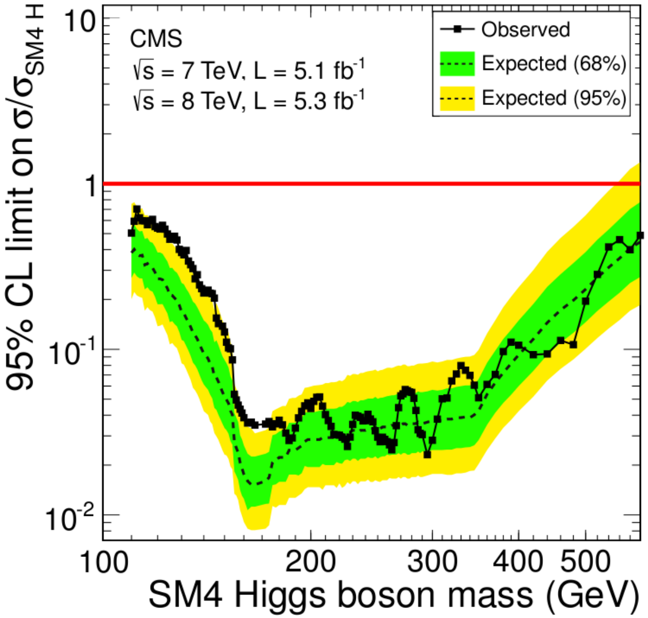
Particle spectrum looks complete: no room for 4th fermion generation!

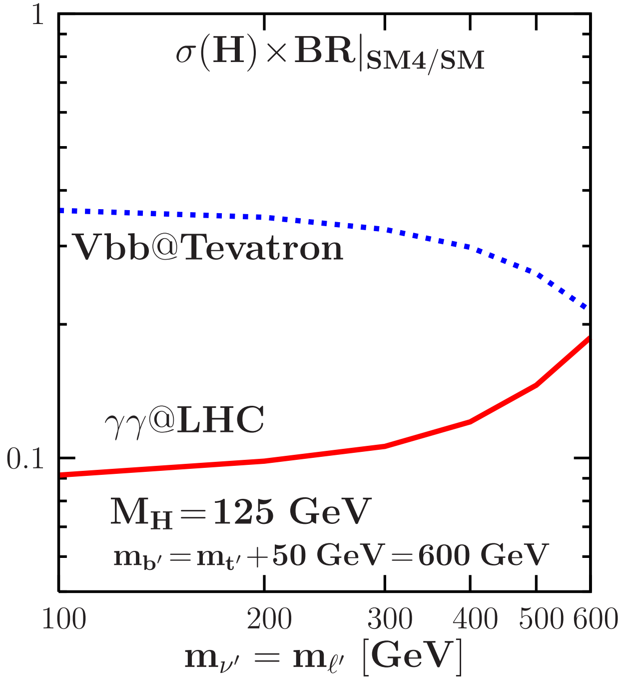
Indeed, an extra doublet of quarks and leptons (with heavy ν') would:

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



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





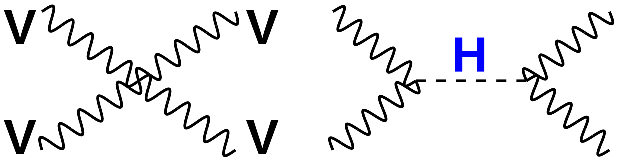
(Direct seach also constraining..) **Lenz....**

4. 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 vacuum

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

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

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

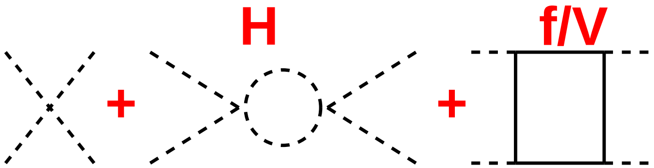
$\Rightarrow$ Degrassi et al., Bezrukov et al.

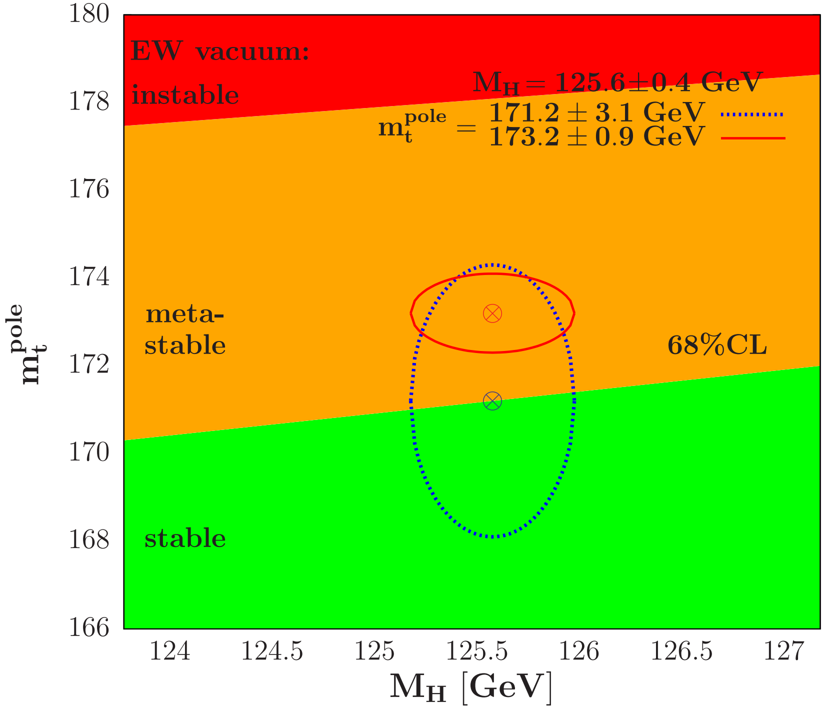
but what is measured m_t at TEV/LHC

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

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

issue needs further studies/checks...





Alekhin....

4. 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 as proved by ’t Hooft and Veltman for SEWSB,**
- **unitary as we have now a Higgs and its mass is rather small,**
- **perturbative up to the Planck scale as again the Higgs is light,**
- **leads to a (meta)stable electroweak vacuum 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:

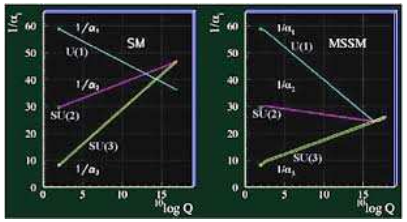
- **“Esthetical” problems with multiple and arbitrary parameters.**
- **“Experimental” problems as it does not explain all seen phenomena.**
- **”A theory consistency” problem: the hierarchy/naturalness problem.**

All indicate that there is beyond the Standard Model physics!

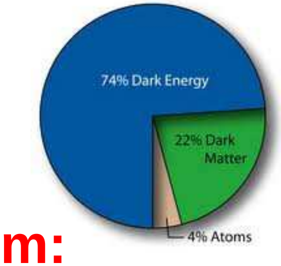
5. The Higgs beyond the Standard Model

There are major theoretical and experimental problems in the SM:

- **does not incorporate masses for the neutrinos (there is no ν_R in SM);**
- **does not explain baryon asymmetry (baryogenesis?) in the universe;**
- **does not incorporate the fourth fundamental interaction, gravity;**
- **does not explain why $\mu^2 < 0$ and has too many (19!) free parameters.**



- **No real unification of the interactions:**
  - **$3 \neq$ gauge groups with $3 \neq$ couplings,**
  - **no meeting of the couplings in SU(5).**

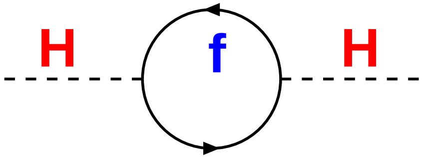


- **No solution to the Dark Matter problem:**
  - **25% of the universe made by Dark Matter,**
  - **no stable, neutral, weak, massive particle.**

- **Above all: there is the hierarchy or naturalness problem:**

radiative corrections to M_H in SM with a cut–off $\Lambda = M_{NP} \approx M_P$

$$\Delta M_H^2 \equiv$$



$$\propto \Lambda^2 \approx (10^{18}\,\mathrm{GeV})^2!$$

M_H prefers to be close to the high scale than to the EWSB scale...

5. The Higgs beyond the Standard Model

Three main avenues for solving the hierarchy or naturalness problems (stabilising the Higgs mass against high scales) have been proposed.

I. Compositeness/substructure:

there is yet another layer in structure!

All particles are not elementary ones.

Technicolor: as QCD but at TeV scale.

$\Rightarrow$ H bound state of two fermions

(no more spin–0 fundamental state).

$\Rightarrow$ H properties $\neq$ from of SM Higgs.

II. Extra space–time dimensions

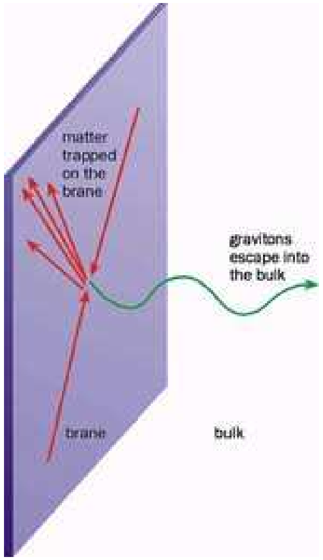
where at least s=2 gravitons propagate.

Gravity: effective scale $\mathrm{M_P^{eff}} \approx \Lambda \approx$ TeV

(and is now $\approx$ included in the game...).

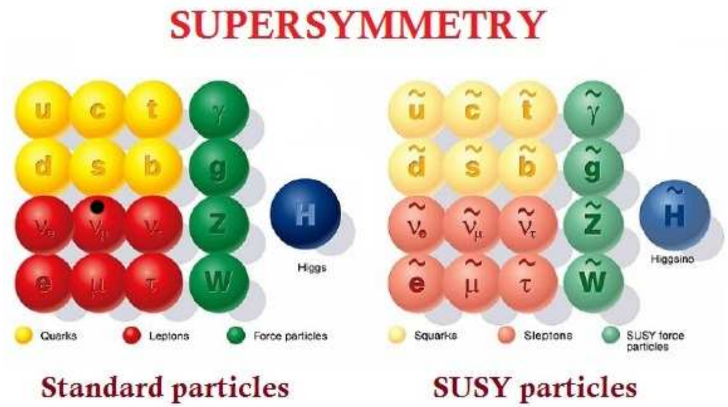
EWSB mechanism needed in addition:

- **same Higgs mechanism as in SM,**
- **but possibility of Higgsless mode!**



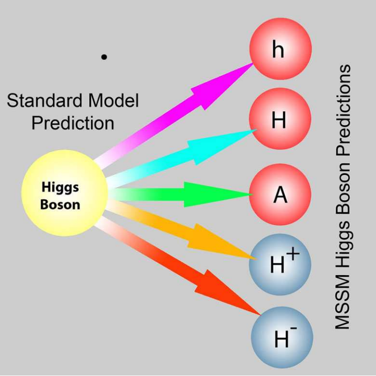
5. The Higgs beyond the Standard Model

III. Supersymmetry: doubling the world.



- SUSY = most attractive SM extension:

– links s=$\frac{1}{2}$ fermions to s=1 bosons,
– links internal/space-time symmetries,
– if made local, provides link to gravity!
– naturally present in string theory (toe),
– natural $\mu^2 < 0$: radiative EWSB,
– fixes gauge coupling unification pb,
– has ideal candidate for Dark Matter...



- Needs two scalar doublets for proper and consistent EWSB in the MSSM:

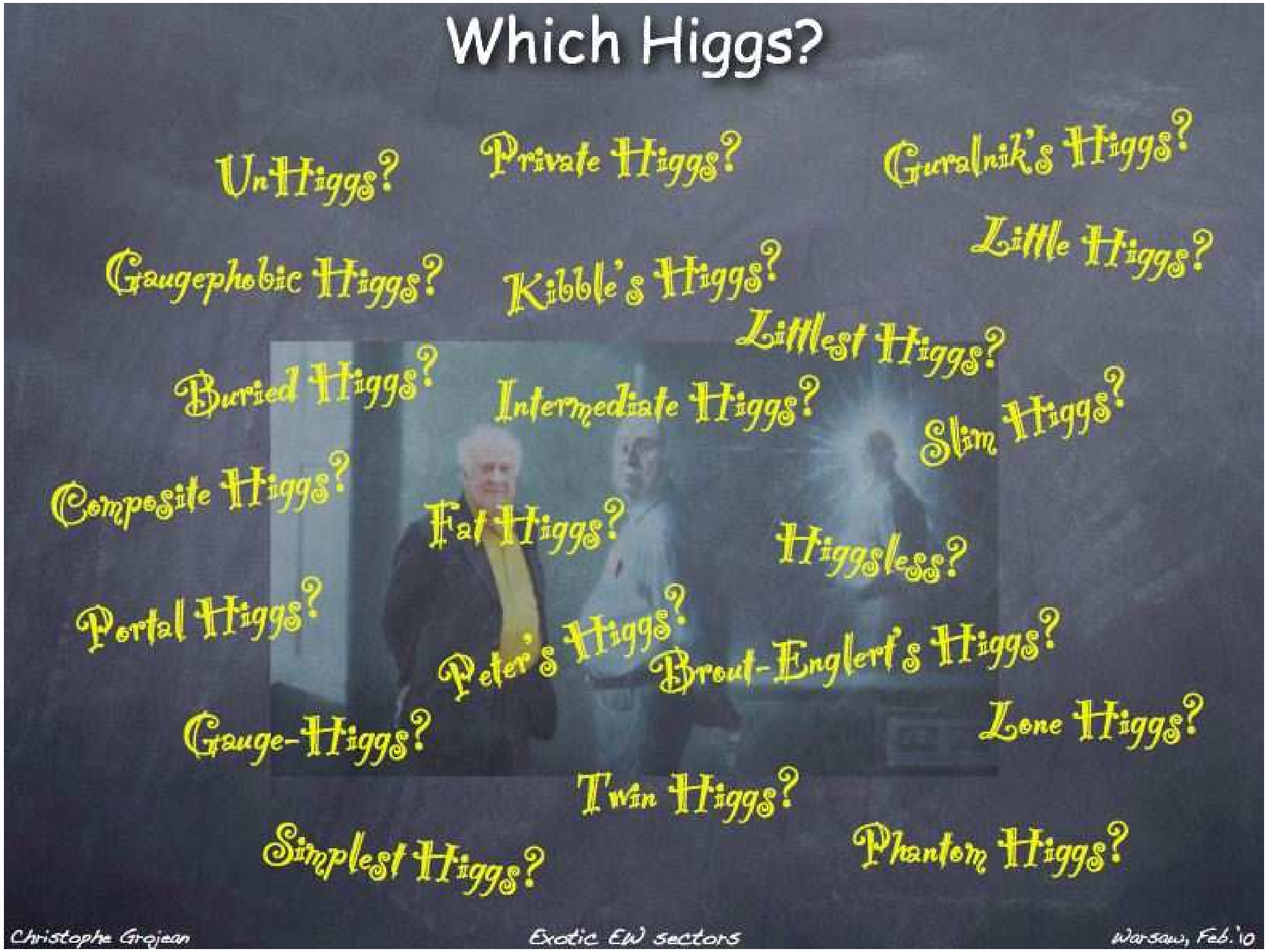
$\Rightarrow$ extended Higgs sector: $\mathrm{h, H, A, H^+, H^-}$ with $\mathrm{h \oplus H \approx H_{SM}}$,
– SUSY $\Rightarrow$ only two basic inputs at tree-level: $\tan\beta = \mathrm{v_2/v_1}, \mathrm{M_A}$,
– SUSY $\Rightarrow$ hierarchical spectrum: $\mathrm{M_h \approx M_Z}$; $\mathrm{M_H \approx M_A \approx M_{H^\pm}}$.
(SUSY scale $\mathrm{M_S}$ pushes $\mathrm{M_h}$ to 130 GeV via radiative corrections).

- Most often decoupling regime: $\mathrm{h \equiv H_{SM}}$, others decouple from W/Z.

5. The Higgs beyond the Standard Model

... and along the avenues, many possible streets, paths, corners ...

Just for EWSB, there are dozens of possibilities for the Higgs sector.



Which scenario is chosen by Nature? The LHC gave a first answer!

5. The Higgs beyond the Standard Model

A) We observe a Higgs boson with a mass of 126 GeV and no other Higgs:

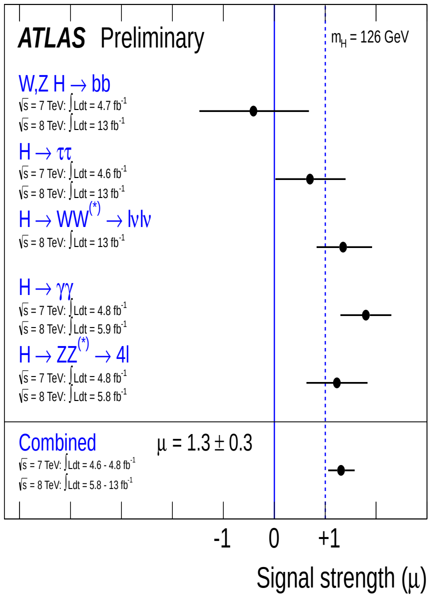
$\sigma\times$BR rates compatible with those expected in the SM

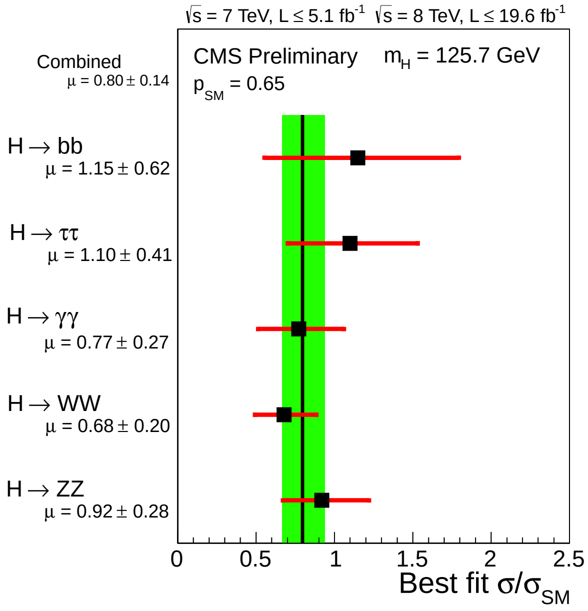
Fit of all LHC Higgs data $\Rightarrow$ agreement at 20–30% level

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

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

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





B) We do not observe any new particle beyond those of SM with Higgs:

profound implications for the most discussed BSM scenarios; they are in:

- **“Mortuary”: Higgsless models, 4th generation, fermio or gauge-phobic.**
- **“Hospital”: Technicolor, composite models, ...**
- **“Trouble” and strongly constrained: extra-dimensions, Supersymmetry,**

Here, I discuss the example of Supersymmetry and the MSSM.

6. The MSSM and its Higgs sector

The MSSM is the most economical low energy SUSY extension of the SM.

It is based on the following simplifying assumptions:

- **Minimal gauge group, the SM one $\mathrm{SU(3)_C \times SU(2)_L \times U(1)}$:**

The SM spin–1 $\mathrm{B, W_i, g_i}$ gauge bosons
and their spin–$\frac{1}{2}$ gaugino partners $\mathrm{\tilde{b}, \tilde{w}, \tilde{g}}$ } ⇒ **put in vector superfields.**

- **Minimal particle content: 3 fermion generations + two Higgs doublets**

(no chiral anomalies, $\sum_\mathrm{f} \mathrm{Q_f} \equiv 0$, and no conjugate $\mathrm{H^*}$ for mass terms):

fermions and their spin–0 $\mathrm{\tilde{f}_{L/R}}$ partners
Higgsses and their spin–$\frac{1}{2}$ $\mathrm{\tilde{h}_{1/2}}$ partners } ⇒ **chiral supermultiplets.**

– current eigenstates $\mathrm{\tilde{f}_{L/R}}$ mix to make the two mass eigenstates $\mathrm{\tilde{f}_{1/2}}$,
– charged/neutral winos+higgsinos ⇒ charginos $\chi^{\pm}_{1,2}$/neutralinos $\chi^{0}_{1,2,3,4}$

- **Discrete and multiplicative symmetry called R–parity is conserved:**

$$\mathrm{R_p} = (-1)^{\mathrm{2s+3B+L}} \Rightarrow \begin{cases} = +1 \text{ for all ordinary SM particles,} \\ = -1 \text{ for all the SUSY particles.} \end{cases}$$

Important consequences: {
– sparticles always produced in pairs,
– decay into odd number of sparticles,
– lightest one (LSP) is absolutely stable.

6. The MSSM and its Higgs sector

- **We need a superpotential to implement the Yukawa interactions**

most general one compatible with SUSY, gauge invariance, R_p, etc..:

$$W = \sum_{i,j} Y^u_{ij} \, \hat{u}^i_R \hat{H}_2 . \hat{Q}^j + Y^d_{ij} \, \hat{d}^i_R \hat{H}_1 . \hat{Q}^j + Y^l_{ij} \, \hat{l}^i_R \hat{H}_1 . \hat{L}^j + \mu \hat{H}_1 . \hat{H}_2$$

– $Y^{u,d,l}_{ij}$ **Yukawa couplings among generations (generalisation of SM),**
– μ **supersymmetric Higgs–higgsino parameter: only additional one!**

At this stage everything is supersymmetric and uniquely specified!

But need to break SUSY ⇒ soft-breaking not to have Λ^2 terms in M_H:
introduce a collection of soft–SUSY breaking terms of dims. 2 and 3:

$$\mathcal{L}_{\rm gaugino} = \frac{1}{2}\left[M_1 \tilde{b}\tilde{b} + M_2 \Sigma^3_{a=1} \tilde{w}^a \tilde{w}_a + M_3 \Sigma^8_{a=1} \tilde{g}^a \tilde{g}_a \; + \; {\rm h.c.} \right]$$

$$\mathcal{L}_{\rm sf.} = \Sigma_i m^2_{\tilde{Q},i} \tilde{Q}^\dagger_i \tilde{Q}_i + m^2_{\tilde{L},i} \tilde{L}^\dagger_i \tilde{L}_i + m^2_{\tilde{u},i} |\tilde{u}_{R_i}|^2 + m^2_{\tilde{d},i} |\tilde{d}_{R_i}|^2 + m^2_{\tilde{l},i} |\tilde{l}_{R_i}|^2$$

$$\mathcal{L}_{\rm Higgs} = m^2_2 H^\dagger_2 H_2 + m^2_1 H^\dagger_1 H_1 + B\mu (H_2 . H_1 + {\rm h.c.})$$

$$\mathcal{L}_{\rm tr} = \Sigma_{i,j} \left[A^u_{ij} Y^u_{ij} \tilde{u}_{R_i} H_2 . \tilde{Q}_j + A^d_{ij} Y^d_{ij} \tilde{d}_{R_i} H_1 . \tilde{Q}_j + A^l_{ij} Y^l_{ij} \tilde{l}_{R_i} H_1 . \tilde{L}_j + {\rm h.c.} \right]$$

Then life becomes complicated and problematic with this potential!

⇒ **too many free parameters (+105!) and thus not very predictive;**
⇒ **leads generically to problematic pheno (FCNC, CPV, CCB, $\not{M}_{\not{Z}}$).**

6. The MSSM and its Higgs sector

A more phenomenologically viable MSSM is defined by assuming:

- all soft SUSY–breaking parameters are real (no new CP violation);
- masses and trilinear couplings for sfermions diagonal (no FCNC);
- 1st/2d sfermion generation universality (no problem with Kaons..).

Define phenomenological MSSM (pMSSM) with 22 free parameters:

$\tan\beta$: the ratio of the vevs of the two–Higgs doublet fields;
$m^2_{H_u}, m^2_{H_d}$: the two soft-SUSY breaking Higgs mass parameters;
M_1, M_2, M_3: the bino, wino and gluino mass parameters;
$m_{\tilde{q}}, m_{\tilde{u}_R}, m_{\tilde{d}_R}, m_{\tilde{l}}, m_{\tilde{e}_R}$: 1st/2d generation sfermion mass parameters;
$m_{\tilde{Q}}, m_{\tilde{t}_R}, m_{\tilde{b}_R}, m_{\tilde{L}}, m_{\tilde{\tau}_R}$: third generation sfermion mass parameters;
A_t, A_b, A_τ: the third generation trilinear couplings;
A_u, A_d, A_e: the first/second generation trilinear couplings.

In fact, a much simpler situation in the pMSSM compared to general case:

- You can trade $m^2_{H_u}, m^2_{H_d}$ with more "physical" μ and M_A parameters.
- A_u, A_d, A_e in general not relevant for phenomenology (come with m_f).
- If focus on given sector (Higgs, $\chi, \tilde{f}$) only few parameters to deal with...

$\Rightarrow$ **phenomenologically more viable model and more predictive!**

6. The MSSM and its Higgs sector

All MSSM problems solved with universal boundary conditions at high scale:

$\not{\rm SUSY}$ in hidden sector communicating with visible through gravity only!

$\Rightarrow$ universal soft $\not{\rm SUSY}$ terms emerge if interactions are "flavor–blind".

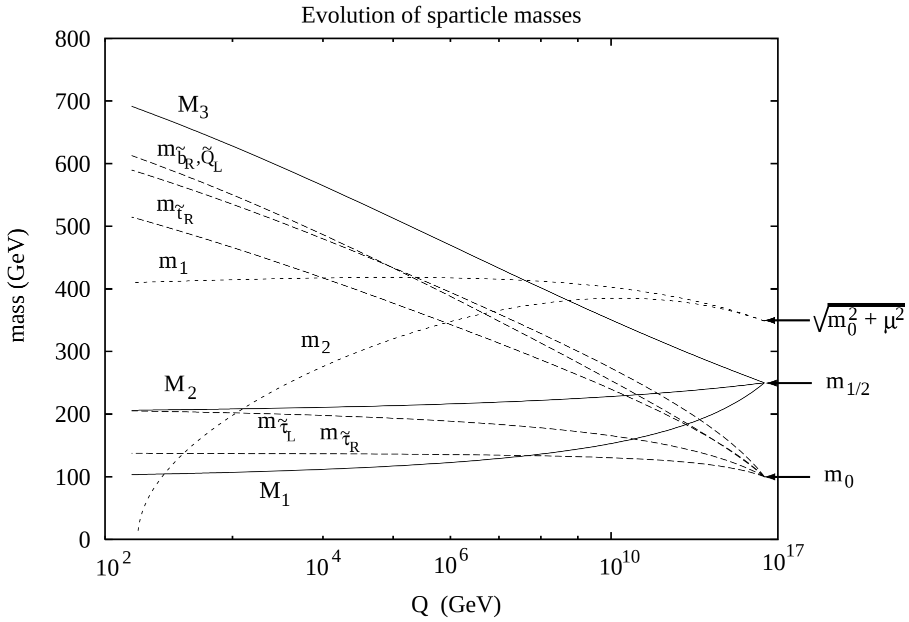
Besides $g_{1,2,3}$ unification which fix the GUT scale $M_{\rm GUT} \sim 2 \cdot 10^{16}$ GeV:

unification of gaugino, scalar masses and trilinear cplgs at $Q = M_{\rm GUT}$.

- $M_1 = M_2 = M_3 \equiv m_{1/2}$
- $M_{\tilde{Q}_i} = M_{\tilde{L}_i} = M_{H_i} \equiv m_0$
- $A^u_{ij} = A^d_{ij} = A^l_{ij} \equiv A_0\, \delta_{ij}$
- B and μ^2 from correct EWSB (and minimisation of $V_{\rm Higgs}$):

$$\mu^2 = \frac{1}{2}\left[t_{2\beta}\left(m^2_{H_u} t_\beta - \frac{m^2_{H_d}}{t_\beta}\right) - M_Z^2\right]$$

$$B\mu = \frac{1}{2} s_{2\beta}\left[m^2_{H_u} + m^2_{H_d} + 2\mu^2\right]$$



mSUGRA: only 4 free parameters+sign: $\tan\beta, m_{1/2}, m_0, A_0, {\rm sign}(\mu)$

$\Rightarrow$ all soft parameters at scale $M_{\rm SUSY} = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$ obtained through RGEs

$\Rightarrow$ radiative EWSB as $M^2_{H_2} < 0$ at scale M_Z from $t/\tilde{t}$ loops: more natural!

6. The MSSM and its Higgs sector

Scalar EWSB potential V_H in terms of $\overline{m}^2_{1,2} = |\mu|^2 + m^2_{H_{1,2}}, \overline{m}^2_3 = B\mu$

$$V_H = \overline{m}_1^2 |H_1^0|^2 + \overline{m}_2^2 |H_2^0|^2 + \overline{m}_3^2 (H_1^0 H_2^0 + \mathrm{hc}) + \frac{M_Z^2}{4v^2}(|H_1^0|^2 - |H_2^0|^2)^2$$

- **Quartic couplings given by g_i ⇒ 3 free parameters $\overline{m}^2_{1,2,3}$ instead of 6!**
- **$\bar{m}_{1,2}$ real and $\bar{m}_{1,2}$ complex but phase rotated ⇒ V_H conserves CP!**
- **If $B\mu = 0$, $\bar{m}^2_{1,2} \geq 0$; $V_H = 0$ only if $\langle H_1^0 \rangle = \langle H_2^0 \rangle = 0$: SSB ⇒ $\overline{m}_{1,2,3} \neq 0$**

⇒ connection of electroweak symmetry breaking and SUSY breaking!

Physical Higgs masses and mixing angle α from minimisation of V_H:

$$M_A^2 = -\bar{m}_3^2(\tan\beta + \cot\beta) = -2\bar{m}_3^2/\sin 2\beta$$

$$M_{h,H}^2 = \frac{1}{2}\left\{M_A^2 + M_Z^2 \mp \left[(M_A^2 + M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta\right]^{1/2}\right\}$$

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

$$\tan 2\alpha = \frac{-(M_A^2 + M_Z^2)\sin 2\beta}{(M_Z^2 - M_A^2)\cos 2\beta} = \tan 2\beta \, \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2} \quad \left(-\frac{\pi}{2} \leq \alpha \leq 0\right)$$

Gives important constraints on the MSSM h boson masses (tree-level):

$$M_H > M_A, M_{H^\pm} > M_W \,, M_h \leq \min(M_A, M_Z) \cdot |\cos 2\beta| \leq M_Z$$

The relations are broken by large radiative corrections in the HIggs sector.

6. The MSSM and its Higgs sector

Life is more complicated and radiative corrections have to be included.

The CP-even Higgses described by 2×2 matrix including corrections:

$$\mathbf{M_S^2} = \mathbf{M_Z^2}\begin{pmatrix} c_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & s_\beta^2 \end{pmatrix} + \mathbf{M_A^2}\begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + \begin{pmatrix} \Delta\mathcal{M}_{11}^2 & \Delta\mathcal{M}_{12}^2 \\ \Delta\mathcal{M}_{12}^2 & \Delta\mathcal{M}_{22}^2 \end{pmatrix}$$

and the two Higgs masses and the mixing angle α are given by:

$$\mathbf{M_{h/H}^2} = \tfrac{1}{2}\left(\mathbf{M_A^2} + \mathbf{M_Z^2} + \mathbf{C_+} \mp \sqrt{\mathbf{M_A^4} + \mathbf{M_Z^4} - \mathbf{2M_A^2 M_Z^2 c_{4\beta}} + \mathbf{C}}\right)$$

$$\alpha = \frac{\mathbf{2}\boldsymbol{\Delta}\mathcal{M}_{\mathbf{12}}^{\mathbf{2}} - (\mathbf{M_A^2} + \mathbf{M_Z^2})\mathbf{s}_\beta}{\mathbf{C_-} + (\mathbf{M_Z^2} - \mathbf{M_A^2})\mathbf{c_{2\beta}} + \sqrt{\mathbf{M_A^4} + \mathbf{M_Z^4} - \mathbf{2M_A^2 M_Z^2 c_{4\beta}} + \mathbf{C}}}$$

with

$$\mathbf{C_\pm} = \boldsymbol{\Delta}\mathcal{M}_{\mathbf{11}}^{\mathbf{2}} \pm \boldsymbol{\Delta}\mathcal{M}_{\mathbf{22}}^{\mathbf{2}}$$

$$\mathbf{C} = \mathbf{4}\boldsymbol{\Delta}\mathcal{M}_{\mathbf{12}}^{\mathbf{4}} + \mathbf{C_-^2} - \mathbf{2}(\mathbf{M_A^2} - \mathbf{M_Z^2})\mathbf{C_- c_{2\beta}} - \mathbf{4}(\mathbf{M_A^2} + \mathbf{M_Z^2})\boldsymbol{\Delta}\mathcal{M}_{\mathbf{12}}^{\mathbf{2}}\mathbf{s_{2\beta}}$$

The dominant corrections come from stop/top sector with a leading term:

$$\boldsymbol{\Delta}\mathcal{M}_{\mathbf{11/12}}^{\mathbf{2}} \sim \mathbf{0}\,,\ \boldsymbol{\Delta}\mathcal{M}_{\mathbf{22}}^{\mathbf{2}} \sim \epsilon = \frac{\mathbf{3\,\bar{m}_t^4}}{\mathbf{2\pi^2 v^2}\sin^{\mathbf{2}}\beta}\left[\log\frac{\mathbf{M_S^2}}{\mathbf{\bar{m}_t^2}} + \frac{\mathbf{X_t^2}}{\mathbf{M_S^2}}\left(\mathbf{1} - \frac{\mathbf{X_t^2}}{\mathbf{12\,M_S^2}}\right)\right]$$

still a simple picture but with a few additional parameters $\mathrm{M_S}, \mathrm{X_t}$...

7. Implications of the discovery for the MSSM

Summary: MSSM has two doublets $H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$ and $H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$,

After EWSB (which can be made radiative: more elegant than in SM):

three dof to make $W_L^\pm, Z_L \Rightarrow$ 5 physical states left out: $h, H, A, H^\pm$

Only two free parameters at tree–level: $\tan\beta, M_A$ but rad. cor. important:

$$M_h \lesssim M_Z |\cos 2\beta| + RC \lesssim 130 \text{ GeV} \ , \ \ M_H \approx M_A \approx M_{H^\pm} \lesssim M_{EWSB}$$

– Couplings of h, H to VV are suppressed; no AVV couplings (CP).

– For $\tan\beta \gg 1$: couplings to b (t) quarks enhanced (suppressed).

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\sin\alpha}{\cos\beta} \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\frac{\sin\alpha}{\sin\beta} \to 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$	0

In the decoupling limit: MSSM reduces to SM but with a light SM Higgs.

this decoupling limit occurs in many extensions....

At tan$\beta \gg$1, one SM–like and two CP–odd like Higgses with cplg to b,τ

$$M_A \leq M_h^{max} \Rightarrow h \equiv A, H \equiv H_{SM} \ , \ M_A \geq M_h^{max} \Rightarrow H \equiv A, h \equiv H_{SM}$$

7. Implications of the discovery for the MSSM

The mass value 125 GeV is rather large for the MSSM h boson,

$\Rightarrow$ one needs from the very beginning to almost maximize it...

Maximizing M_h is maximizing the radiative corrections; at 1-loop:

$$M_h \xrightarrow{M_A \gg M_Z} M_Z|\cos 2\beta| + \frac{3\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{M_S^2}\left(1-\frac{X_t^2}{12M_S^2}\right)\right]$$

- **decoupling regime with $M_A \sim \mathcal{O}$(TeV);**
- **large values of tan$\beta \gtrsim 10$ to maximize tree-level value;**
- **maximal mixing scenario: $X_t = \sqrt{6}M_S$;**
- **heavy stops, i.e. large $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$;**

we choose at maximum $M_S \lesssim 3$ TeV, not to have too much fine-tuning....

- **Do the complete job: two-loop corrections and full SUSY spectrum**
  - **Use RGE codes (Suspect) with RC in $\overline{\rm DR}$/compare with FeynHiggs (OS**

Perform a full scan of the phenomenological MSSM with 22 free parameter

- **determine the regions of parameter space where $123 \leq M_h \leq 129$ GeV**

(3 GeV uncertainty includes both “experimental” and “theoretical” error)

- **require h to be SM–like: $\sigma(h) \times BR(h) \approx H_{SM}$ ($H = H_{SM})$ later)**

Many anlayses! Here, the one from Arbey et al. 1112.3028+1207.1348

7. Implications of the discovery for the MSSM

Main results:

- **Large M_S values needed:**

– $M_S \approx 1$ TeV: only maximal mixing

– $M_S \approx 3$ TeV: only typical mixing.

- **Large tanβ values favored**

but tan$\beta \approx 3$ possible if $M_S \approx 3$TeV

How light sparticles can be with the constraint $M_h = 126$ GeV?

- **1s/2s gen. $\tilde{q}$ should be heavy...**

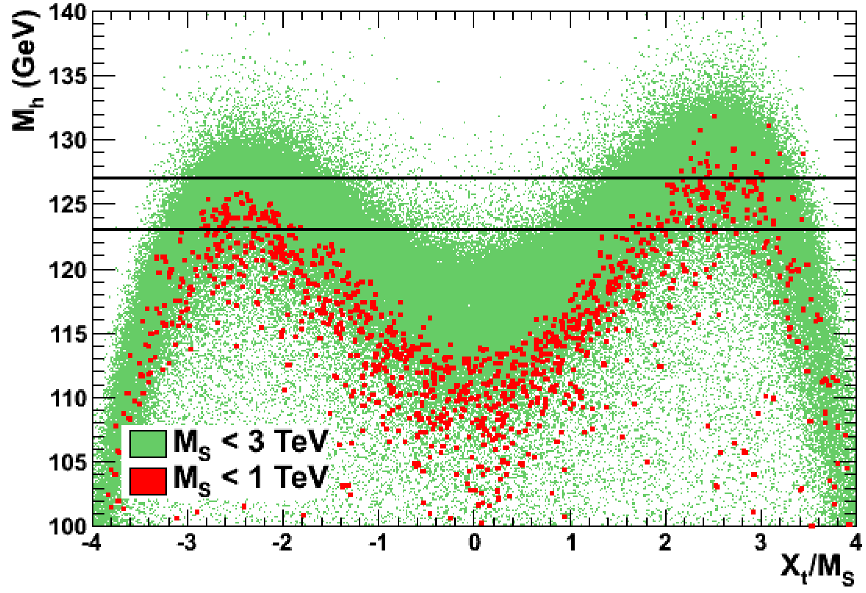
But not main player here: the stops:

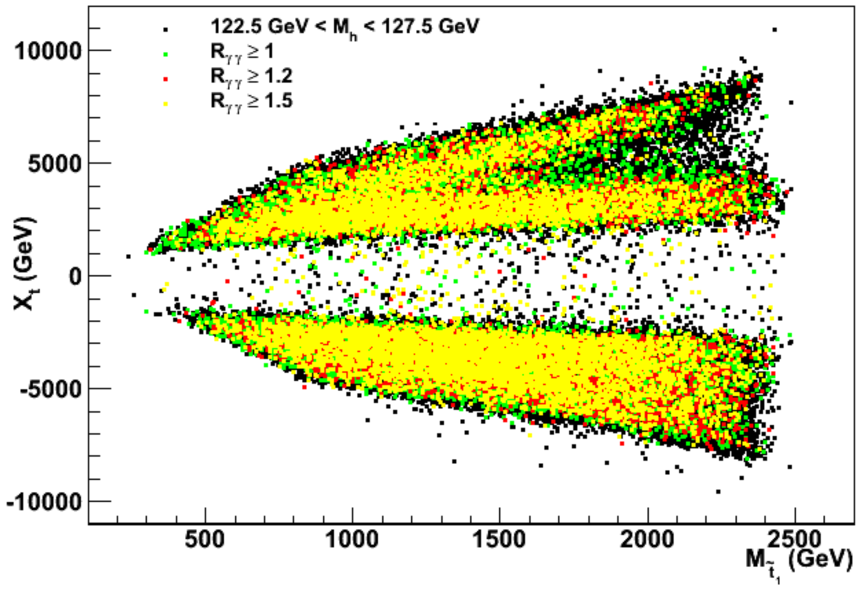
$\Rightarrow m_{\tilde{t}_1} \lesssim 500$ GeV still possible!

(even if M_S is much larger...)

- **M_1, M_2 and μ unconstrained,**
- **non-univ. $m_{\tilde{f}}$: decouple $\tilde{\ell}$ from $\tilde{q}$**

EW sparticles can be still very light but watch out the new LHC limits..





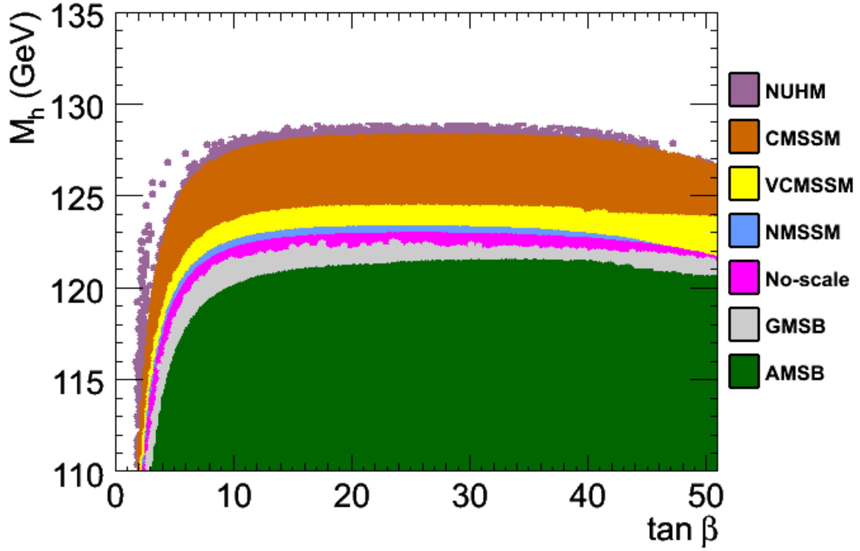
7. Implications of the discovery for the MSSM

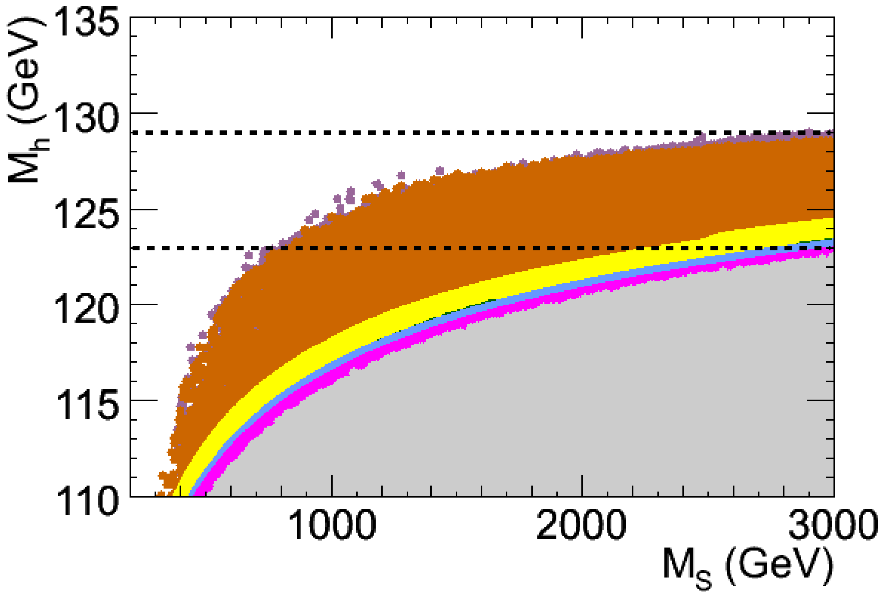
Constrained MSSMs are interesting from model building point of view:

– concrete schemes: SSB occurs in hidden sector $\xrightarrow{\text{gravity,..}}$ MSSM fields
– provide solutions to some MSSM problems: CP, flavor, etc..
– parameters obey boundary conditions $\Rightarrow$ small number of inputs...

- **mSUGRA**: $\tan\beta\ ,\ \mathbf{m_{1/2}}\ ,\ \mathbf{m_0}\ ,\ \mathbf{A_0}\ ,\ \mathrm{sign}(\mu)$
- **GMSB:** $\mathbf{tan}\beta\ ,\ \mathbf{sign}(\mu)\ ,\ \mathbf{M_{mes}}\ ,\ \mathbf{\Lambda_{SSB}}\ ,\ \mathbf{N_{mess\ fields}}$
- **AMSB:**, $\mathbf{m_0}\ ,\ \mathbf{m_{3/2}}\ ,\ \tan\beta\ ,\ \mathrm{sign}(\mu)$

full scans of the model parameters with $\mathbf{123\ GeV \leq M_h \leq 129\ GeV}$





very strong constraints and some (minimal) models ruled out...

7. Implications of the discovery for the MSSM

As the scale $\mathrm{M_S}$ seems to be large, consider two extreme possibilities

- **Split SUSY: allow fine–tuning**

scalars (including $\mathrm{H_2}$) at high scale
gauginos–higgsinos at weak scale
(unification+DM solutions still OK)
$\mathrm{M_h} \propto \log(\mathrm{M_S}/\mathrm{m_t}) \to$ **large**

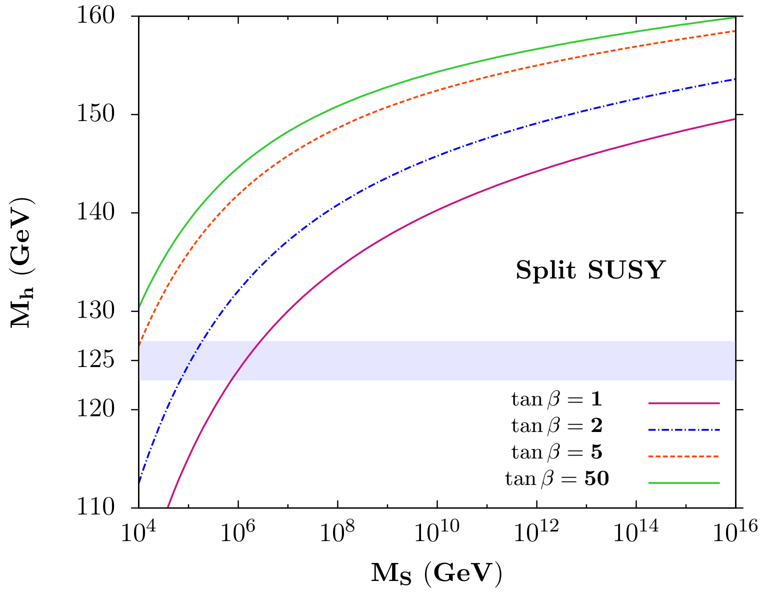
- **SUSY broken at the GUT scale...**

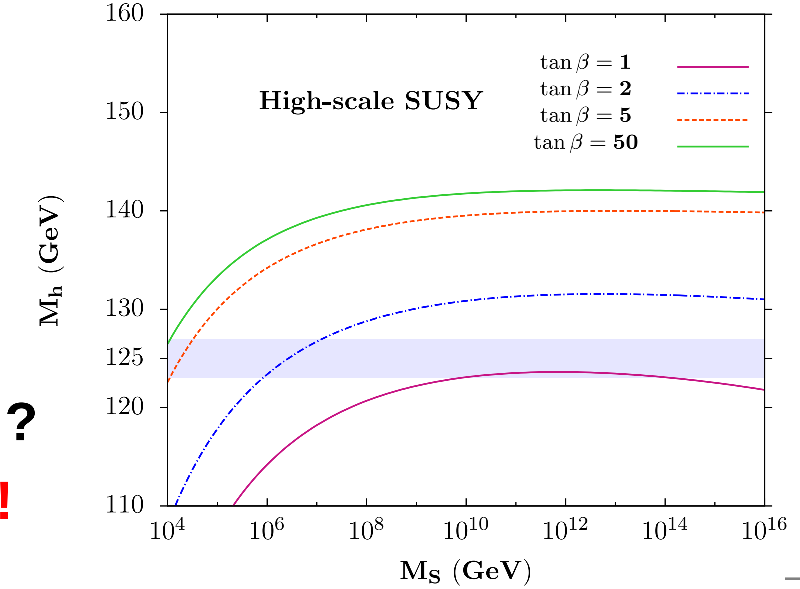
give up fine-tuning and everything else
still, $\lambda \propto \mathrm{M_H^2}$ related to gauge cplgs

$$\lambda(\tilde{\mathrm{m}}) = \frac{\mathrm{g_1^2}(\tilde{\mathrm{m}})+\mathrm{g_2^2}(\tilde{\mathrm{m}})}{8}(1+\delta_{\tilde{\mathrm{m}}})$$

... leading to $\mathrm{M_H}$ =120–140 GeV ...

In both cases small $\tan\beta$ needed...
note 1: $\tan\beta \approx 1$ possible
note 2: $\mathrm{M_S}$ large and not $\mathrm{M_A}$ possible!?
Consider general MSSM with $\tan\beta \approx 1$!

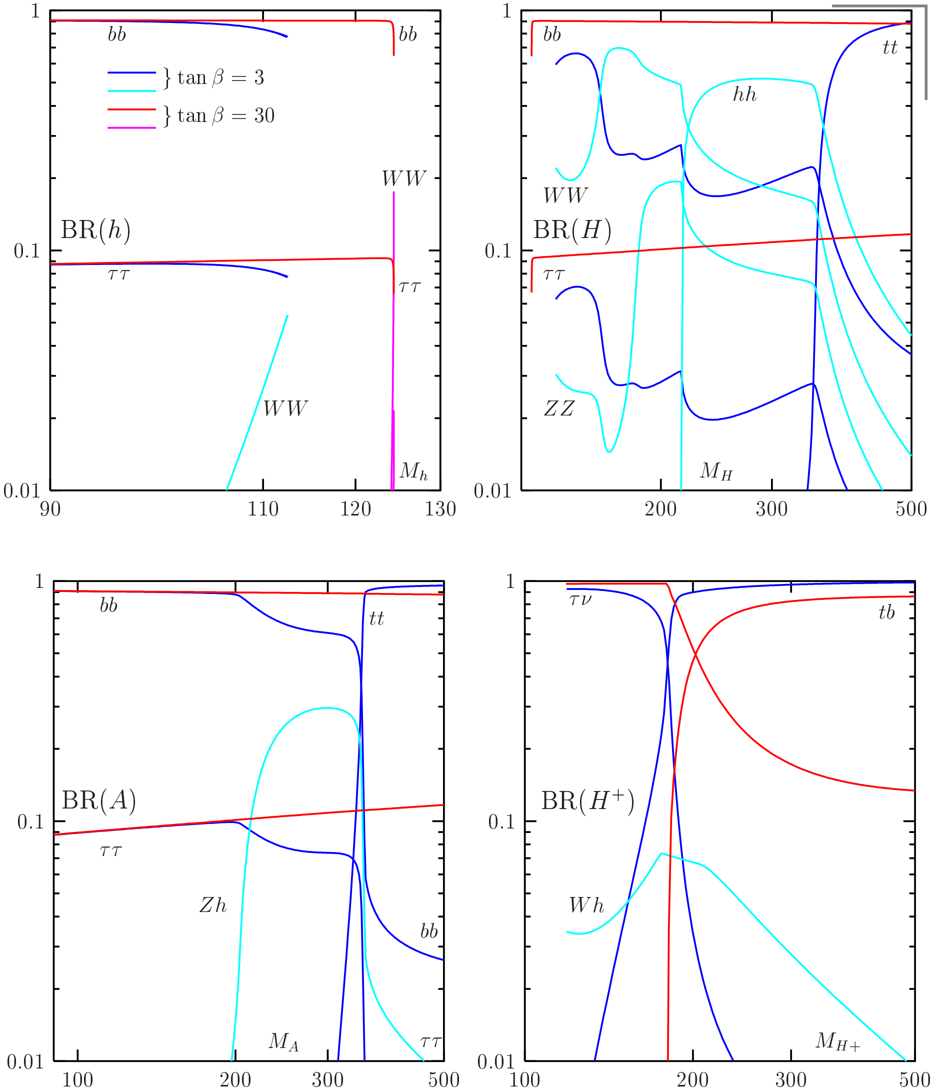




7. Implications of the discovery for the MSSM

What about the heavier MSSM Higgses?

Higgs decays: some general features:



- **h: same as $\mathrm{H_{SM}}$ in general**

(esp. in decoupling limit) if not

$\mathrm{h} \to \mathrm{b\bar{b}}, \tau^+\tau^-$ enhanced for tanβ >1

- **A: only $\mathrm{b\bar{b}}, \tau^+\tau^-$ and $\mathrm{t\bar{t}}$ decays**

(no VV decays, hZ suppressed).

- **H: same as A in general; tanβ $\gg$1**

$\mathrm{WW}, \mathrm{ZZ}, \mathrm{hh}$ decays suppressed.

- **$\mathrm{H}^\pm$: $\tau\nu$ and tb decays**

(depending if $\mathrm{M_{H^\pm}}$ < or > $\mathrm{m_t}$).

Possible new effects from SUSY!!

For tanβ $\gg$1, only decays into b/τ:

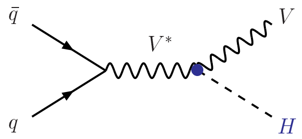
BR: $\Phi \to \mathrm{b\bar{b}} \approx 90\%$, $\Phi \to \tau\tau \approx 10\%$.

For tanβ $\approx$1, many other Higgs channels need to be considered too!

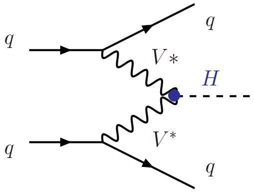
7. Implications of the discovery for the MSSM

SM production mechanisms

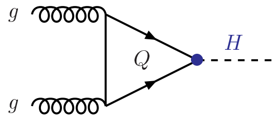
Higgs–strahlung



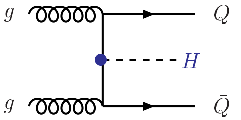
Vector boson fusion

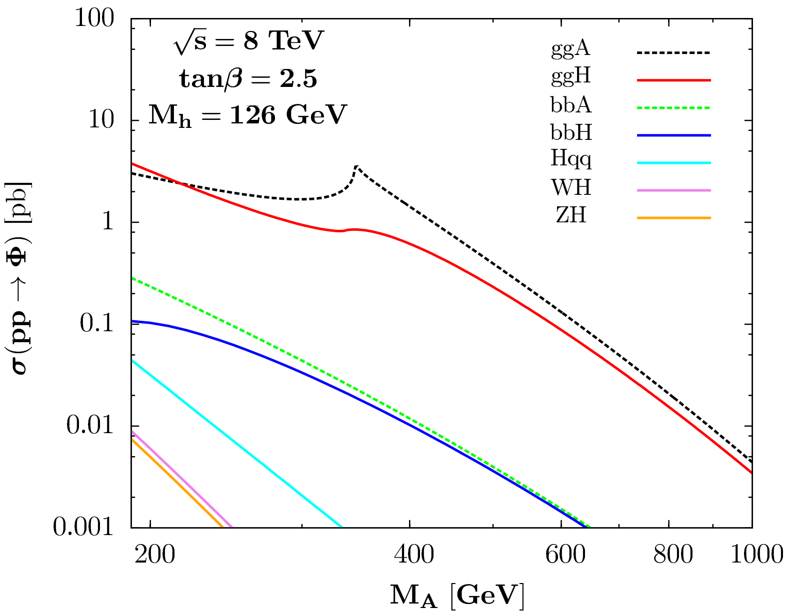


gluon–gluon fusion



in associated with $Q\bar{Q}$





What is different in MSSM

- **All work for CP–even h,H bosons.**

– in ΦV, $qq\Phi$ h/H complementary

– additional mechanism: qq $\to$ A+h/H

- **For $gg \to \Phi$ and $pp \to QQ\Phi$**

– include contribution of b–quarks

– dominant contribution at high tanβ!

- **For pseudoscalar A boson:**

– CP: no ΦA and qqA processes

– $gg \to A$ and $pp \to bbA$ dominant.

- **For charged Higgs boson:**

– $M_H \lesssim m_t$: $pp \to t\bar{t}$ with $t \to H^+b$

– $M_H \gtrsim m_t$: continuum $pp \to t\bar{b}H^-$

At high tanβ values:

– h SM-like with $M_h = 115-130$GeV

– dominant channel: $gg, b\bar{b} \to \Phi \to \tau\tau$

– as well as from $t \to H^+b$ at low $M_{H^\pm}$.

7. Implications of the discovery for the MSSM

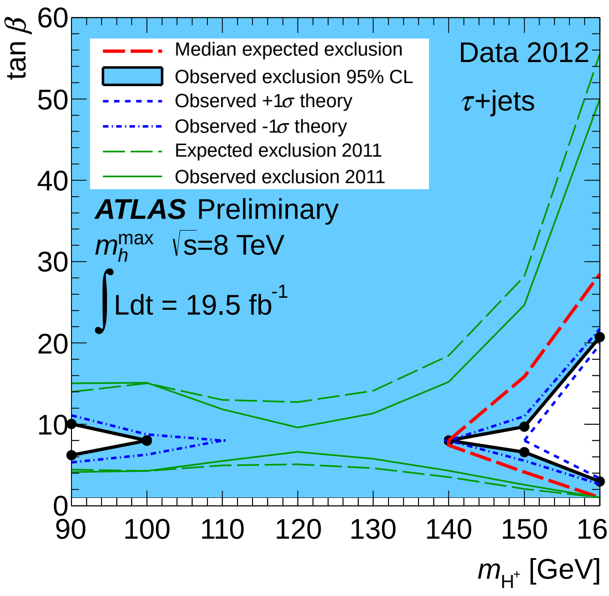
There are other (stringent) constraints on the pMSSM to be included

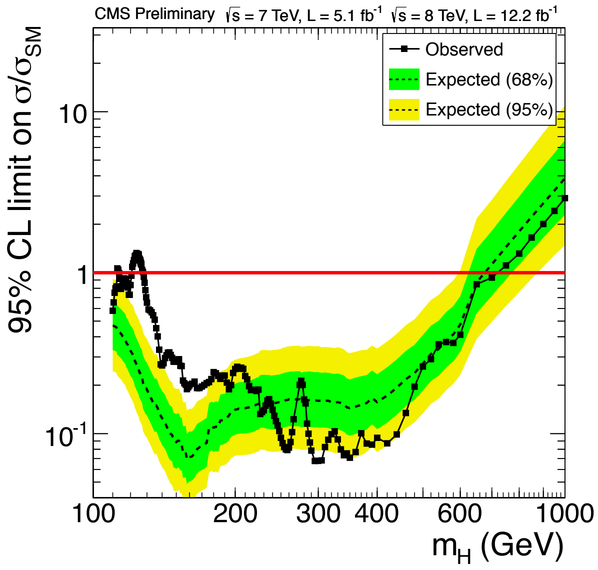
(besides the production/decay rates of the already observed Higgs):

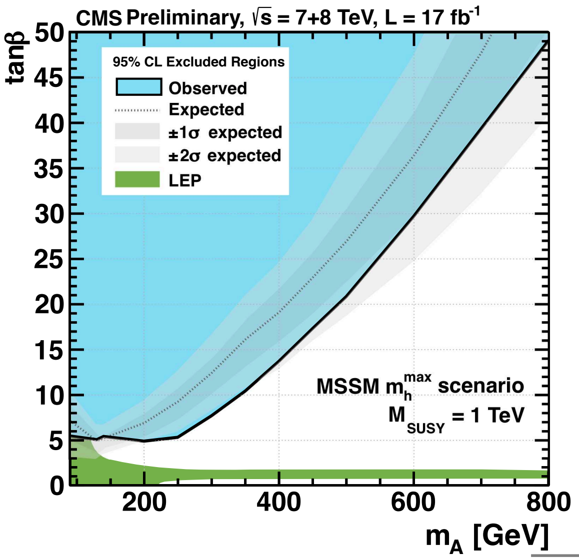
- **Searches for neutral Higgsses in $\mathrm{pp} \to \mathrm{A/H/(h)} \to \tau\tau$ process;**
- **Searches for the charged Higgs boson in $\mathrm{t} \to \mathrm{bH}^+ \to \mathrm{b}\tau\nu$;**
- **non observation of heavier CP–even Higgs bosons in H→ZZ,WW;**
- **one can add searches for new resonances in the H/A→tt channel...**

Besides: one has constraints from flavor, $\mathrm{B_s} \to \mu\mu, \mathrm{b} \to \mathrm{s}\gamma$, g–2 ..

and constraints from sparticle searches and eventually dark matter..







7. Implications of the discovery for the MSSM

Model independent – effective – approach

- **$\tan\beta \lesssim 3$ usually "excluded" by LEP2: $M_h \gtrsim 114$ GeV for BMS with $M_S \approx 1$ TeV.**

Be we can be more relaxed: $M_S \gg M_Z$

$\Rightarrow$ $\tan\beta$ as low as 1 could be allowed!

- **We turn $M_h \approx M_Z |\cos 2\beta| +$RC to**

  RC= 126 GeV - $f(M_A, \tan\beta)$

ie. we "trade" RC with the measured M_h

MSSM with only 2 inputs at HO: $M_A, \tan\beta$

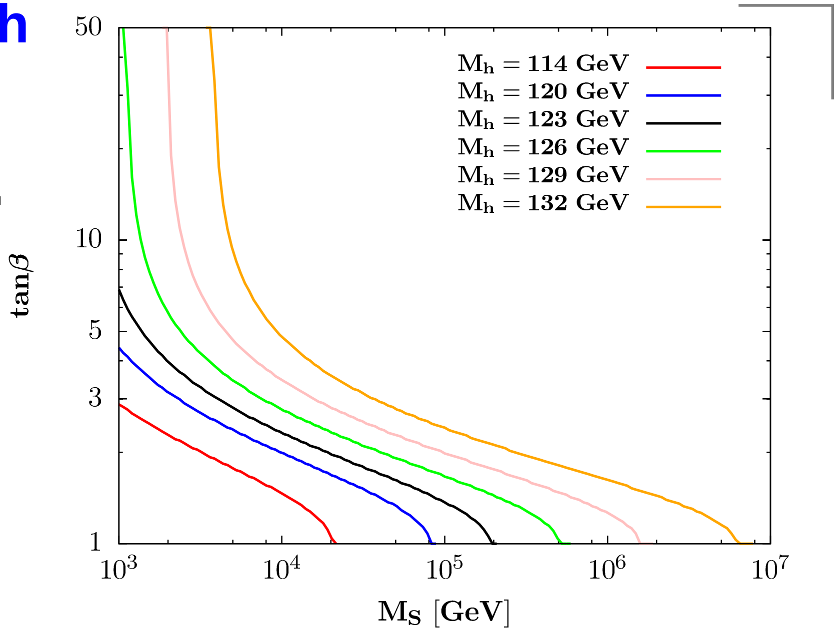
$$M_H^2 = \frac{(M_A^2+M_Z^2-M_h^2)(M_Z^2 c_\beta^2+M_A^2 s_\beta^2)-M_A^2 M_Z^2}{M_Z^2 c_\beta^2+M_A^2 s_\beta^2-M_h^2}$$

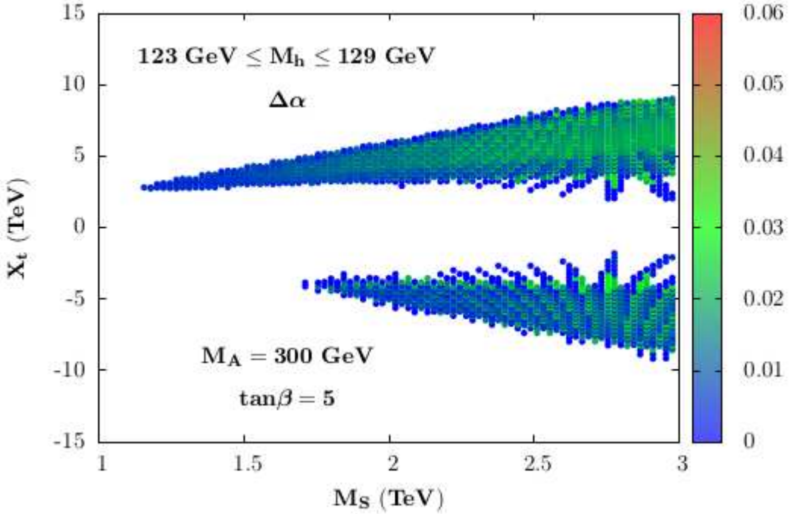
$$\alpha = -\arctan\left(\frac{(M_Z^2+M_A^2)c_\beta s_\beta}{M_Z^2 c_\beta^2+M_A^2 s_\beta^2-M_h^2}\right)$$

$$M_{H^\pm} \simeq \sqrt{M_A^2+M_W^2}$$

Habemus MSSM (hMSSSM):

AD, Maiani,Polosa,Quevillon,Riquer





7. Implications of the discovery for the MSSM

Constraints on the $[\mathrm{M_A}, \tan\beta]$ plane

- **Fits of the h properties $\Rightarrow$**

can be turned into MSSM constraints

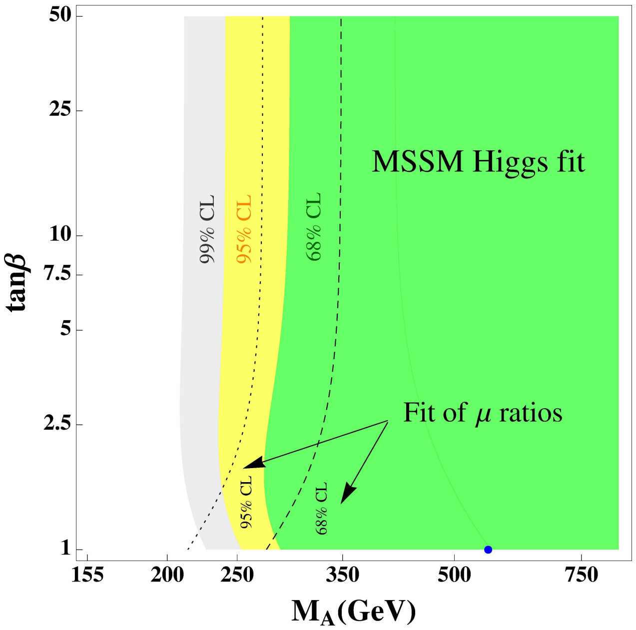
– no important direct SUSY corrections

(no sbottom/sbootom contributions)

– use both signal strengths and ratios

as there is no deviation from SM Higgs:

h SM–like $\Rightarrow \mathrm{M_A} \gtrsim 200-500$ GeV



- **Constraints in the high tanβ region:**

– $\mathrm{t} \to \mathrm{H^+ b} \to \mathrm{b}\tau\nu : \mathrm{M_A} \gtrsim 140$ GeV

– $\mathrm{H/A} \to \tau\tau : \mathrm{M_A} \gtrsim 300$ GeV

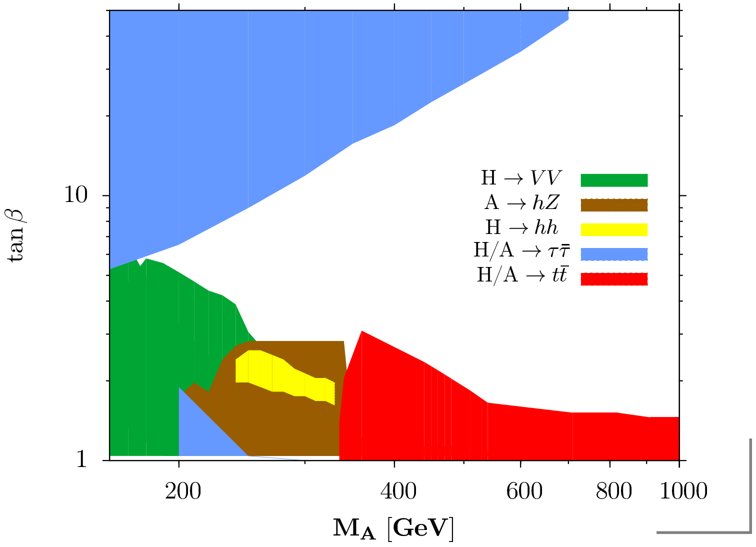
- **Constraints on the low tanβ region:**

– H$\to$WW,ZZ in SM

– H$\to$tt in BSM scenarios

– H$\to$hh and A$\to$hZ..

Plenty of space probed with current data...



7. Implications of the discovery for the MSSM

A 126 GeV Higgs provides information on BSM and SUSY in particular:

- $M_H = 120$ GeV would have been a boring value: everybody OK..
- $M_H = 150$ GeV would be a devastating value: mass extinction..
- $M_H \approx 126$ GeV is interesting: (natural) selection among models..

Implications in the contex of the MSSM:

SUSY spectrum apparently heavy (also backed up by direct searches) except maybe stops and weakly interacting sparticles ($\chi_i^0, \chi_i^\pm, \tilde{\ell}, \tilde{\nu}$).

So, what does it mean?

- Natural or unnatural? not so easy to quantify/judge...
- Multiverse? almost philosophical question...
- Maybe we simply need to go beyond the celebrated MSSM

to increase $M_h \Rightarrow$ NMSSM and more Higgs structure, more matter...

Personal feeling: it is still action time!

- keep searching for SUSY with more focus on stops and EW states
- another hope: discover the heavier Higgs states...

with an open mind towards more complicated/extended scenarios...

8. What next?

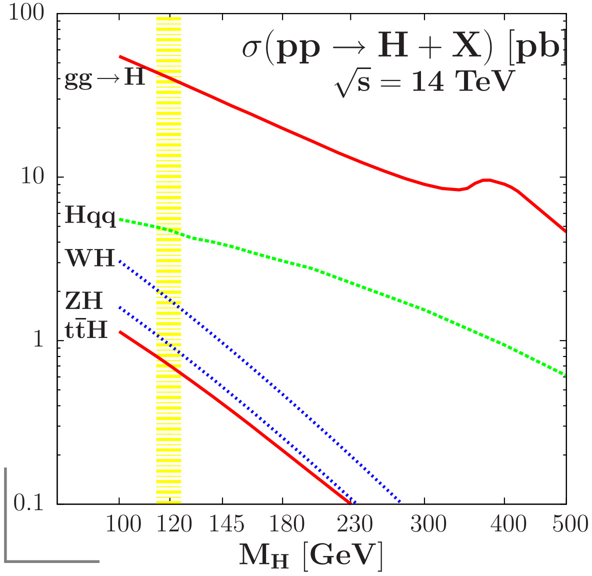
So what should we be doing the next 10–30 years in Particle Physics?

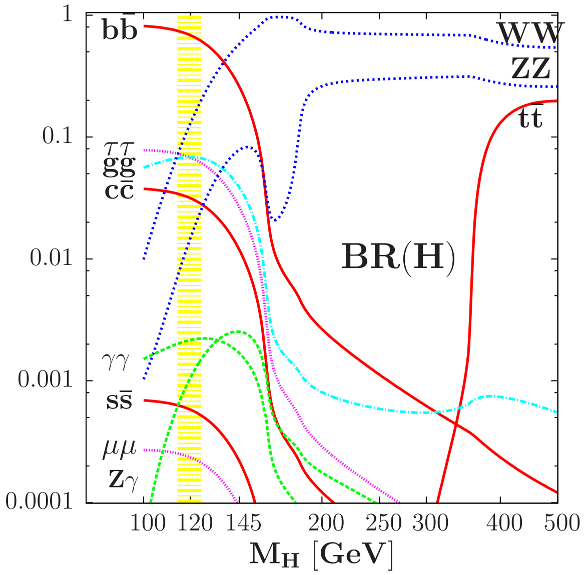
1) Need to check that H is indeed responsible of sEWSB (and SM-like?)

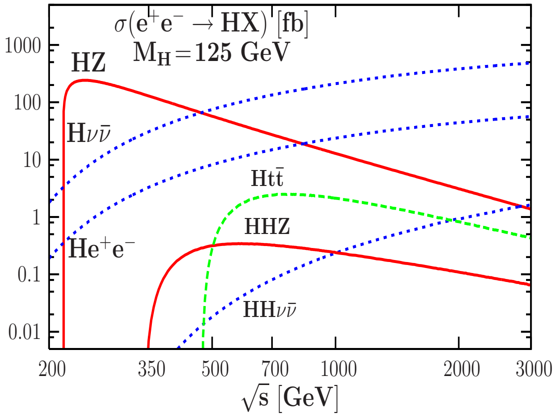
$\Rightarrow$ measure its fundamental properties in the most precise way:

- **its mass and total decay width (invisible width due to dark matter?),**
- **its spin–parity quantum numbers (CP violation for baryogenesis?),**
- **its couplings to fermions and gauge bosons and check if they are only proportional to particle masses (no new physics contributions?),**
- **its self-couplings to reconstruct the potential V_S that makes EWSB.**

Possible for $M_H \approx$ 125 GeV as all production/decay channels useful!







8. What next?

- Look at various H production/decay channels and measure $\mathrm{N_{ev}} = \sigma \times \mathrm{BR}$
- But large errors mainly due to:

– experimental: stats, system., lumi...

– theory: PDFs, HO/scale, jetology...

total error about 15–20% in $gg \to \mathrm{H}$

Hjj contaminates VBF (now 30%)..

$\Rightarrow$ ratios of σxBR: many errors out!

Deal with width ratios $\Gamma_{\mathrm{X}}/\Gamma_{\mathrm{Y}}$

– TH on σ and some EX errors

– parametric errors in BRs

– TH ambiguities from $\Gamma_{\mathrm{H}}^{\mathrm{tot}}$

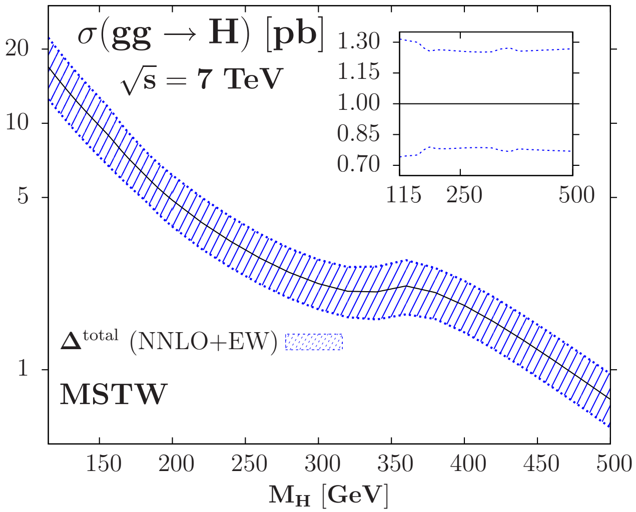
- Achievable accuracy:

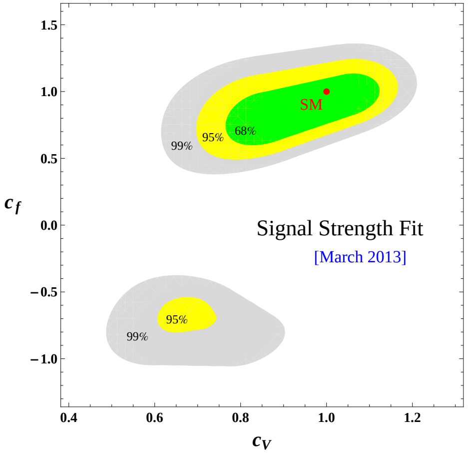
– now: 20–30% on $\mu_{\frac{\gamma\gamma}{\mathrm{VV}}}, \mu_{\frac{\tau\tau}{\mathrm{VV}}}$

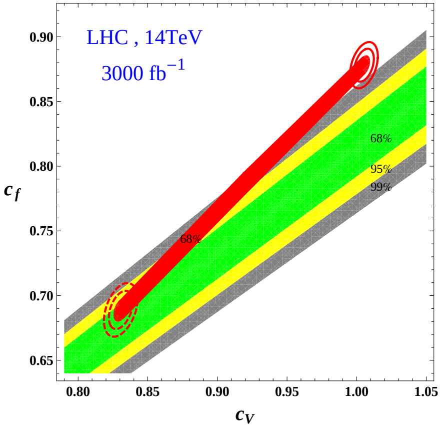
– future: few % at HL–LHC!

Sufficient to probe BSM physics?

Baglio...







Moreau...

8. What next?

- **Total width:** $\Gamma_\mathrm{H} = 4$ MeV, too small to be resolved experimentally.
  – very loose bound from interference gg→ZZ (a factor 10 at most..).
  – no way to access it indirectly (via production rates) in a precise way.
- **Invisible decay width:** more easily accessible at the LHC

Direct measurement:

$\mathrm{q\bar{q} \to HZ}$ and $\mathrm{qq \to Hqq;\ H \to inv}$

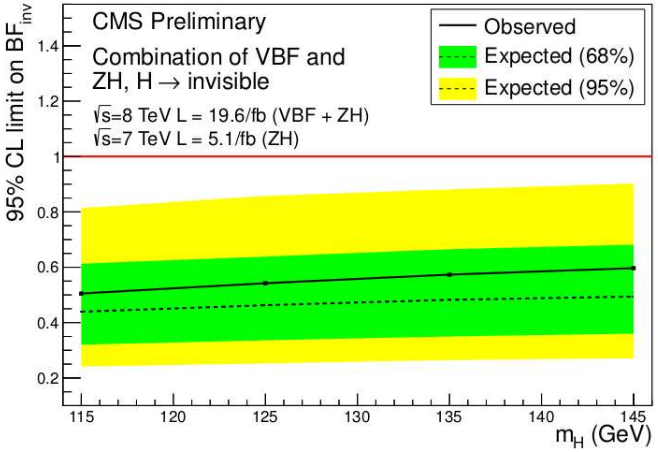
Combined HZ+VBF search from CMS

$\mathrm{BR_{inv}} \lesssim$ 50%@95%CL for SM Higgs

More promising in the future: monojets

$\mathrm{gg \to H + j \to j + \not{E}_T}$

Falkowski...



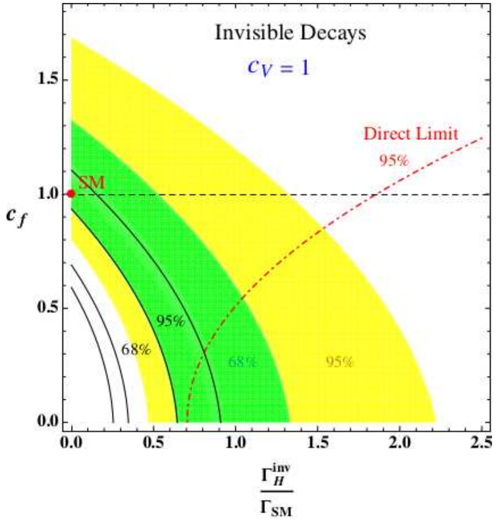
Indirect measurement:

again assume SM–like Higgs couplings

constrain width from signal strengths

$\mathrm{BR_{inv}} \lesssim 50\%$@95%CL for $\mathrm{c_f = c_V = 1}$

Moreau...



Improvement in future: 10% @ HL–LHC?

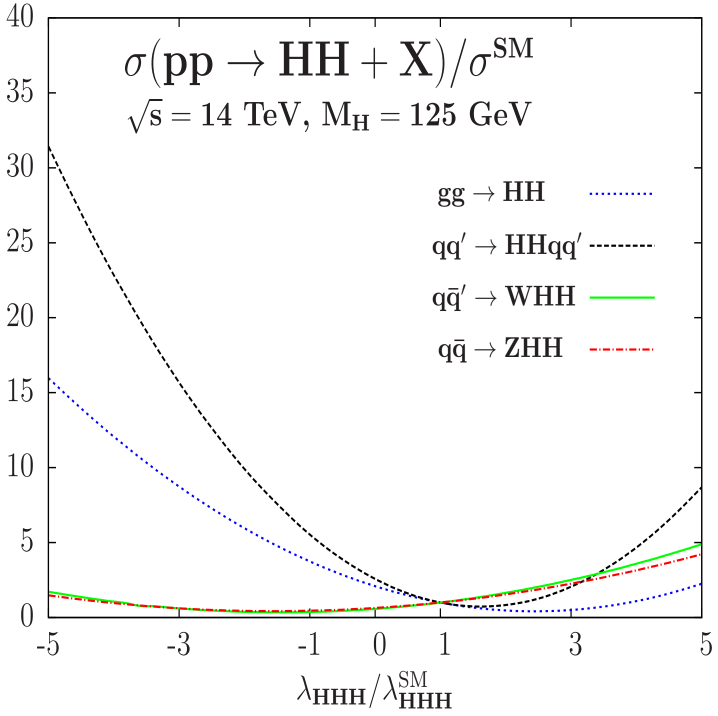
8. What next?

Another challenge: measure Higgs self-couplings and access to V_H.

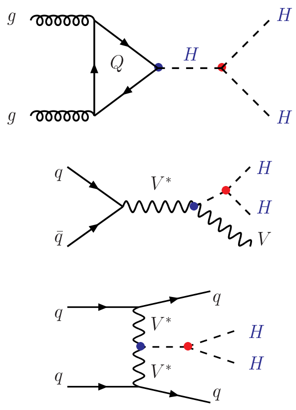
- g_{H^3} from $pp \to HH + X \Rightarrow$
- g_{H^4} from pp$\to$3H+X, hopeless.

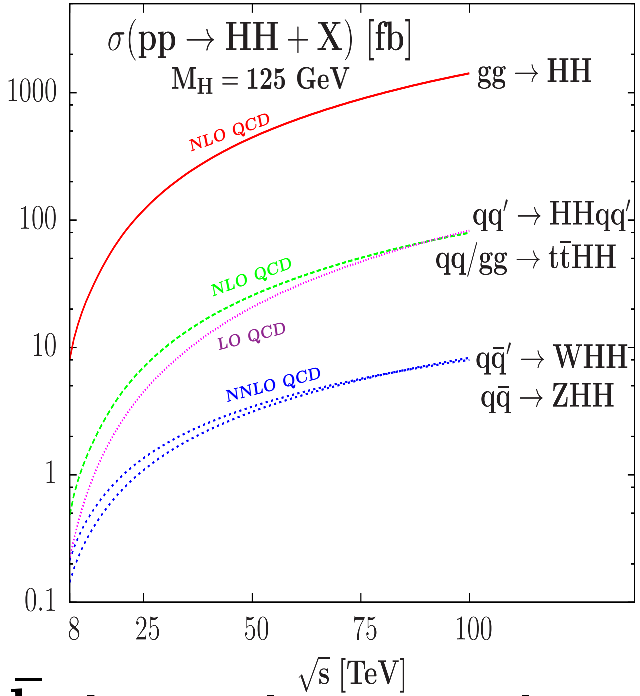
Various processes for HH prod:

only $gg \to HHX$ relevant...



Baglio et al., arXiv:1212.5581



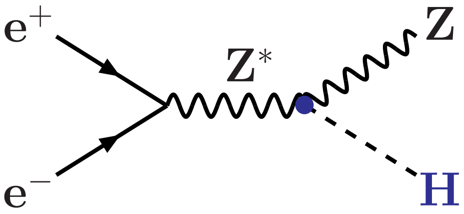


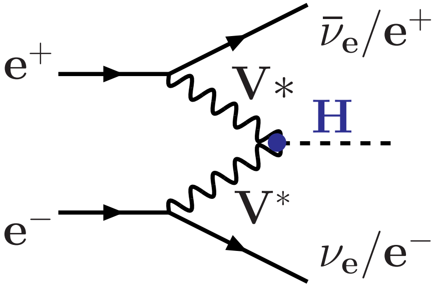
- $H \to b\bar{b}$ decay alone not clean
- $H \to \gamma\gamma$ decay very rare,
- $H \to \tau\tau$ would be possible?
- $H \to WW$ not useful?

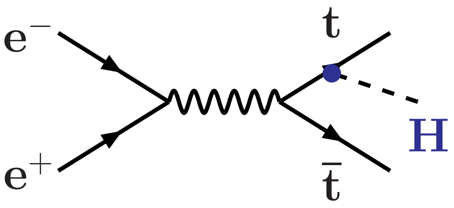
– $bb\tau\tau, bb\gamma\gamma$ viable?

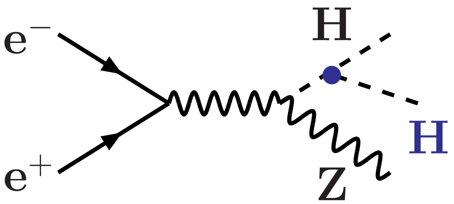
– but needs very large luminosity.

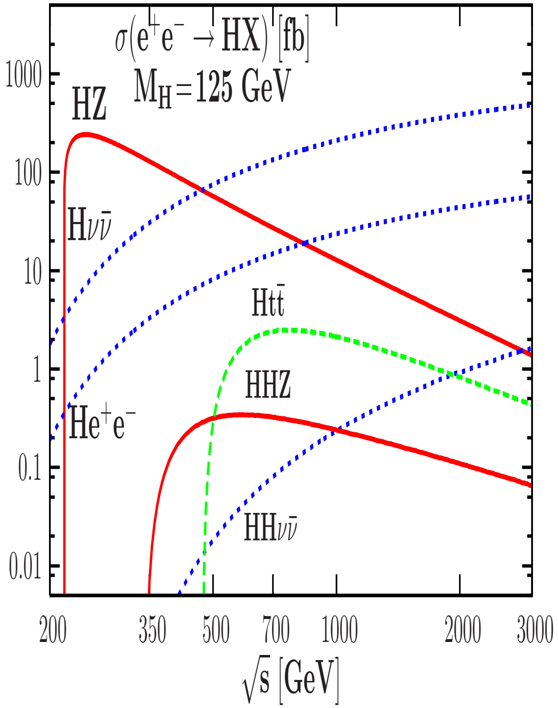
8. What next?











Very precise measurements mostly at $\sqrt{s} \lesssim$ 500 GeV and mainly in $e^+e^- \to ZH$ (with $\sigma \propto 1/s$) and ZHH, ttH

g_{HWW}	± 0.012
g_{HZZ}	± 0.012
g_{Hbb}	± 0.022
g_{Hcc}	± 0.037
$g_{H\tau\tau}$	± 0.033
g_{Htt}	± 0.030
λ_{HHH}	± 0.22
M_H	± 0.0004
Γ_H	± 0.061
CP	± 0.038

⇒ difficult to be beaten by anything else for ≈ 125 GeV Higgs

⇒ welcome to the e^+e^- precision machine!

8. What next?

2) Fully probe the TeV scale that is relevant for the hierarchy problem
⇒ continue to search for heavier Higgses and new (super)particles.

- **Search for heavier SUSY Higgses:**

– $\mathrm{pp} \to \mathrm{H/A} \to \tau\tau, \mathrm{t\bar{t}}$

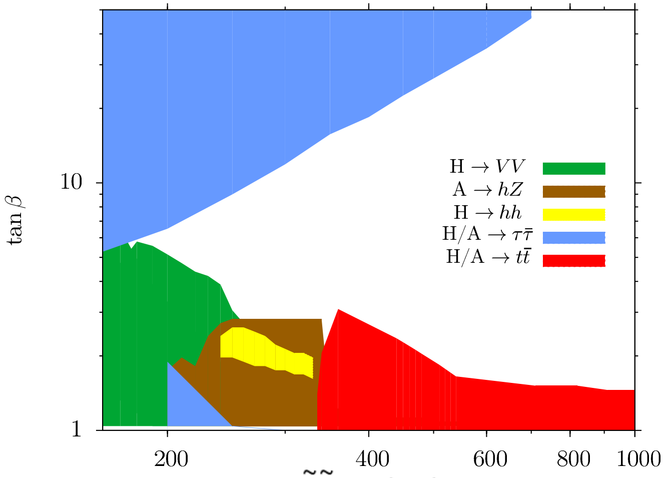
– $\mathrm{pp} \to \mathrm{H} \to \mathrm{WW}, \mathrm{ZZ}, \mathrm{hh}$

– $\mathrm{pp} \to \mathrm{A} \to \mathrm{hZ}$

– $\mathrm{pp} \to \mathrm{H^- t} \to \mathrm{Wb}\tau\nu$

⇒ extend reach as much as possible.

AD, Maiani,Polosa,Quevillon (2013) ⇒



- **Search for supersymmetric particles:**

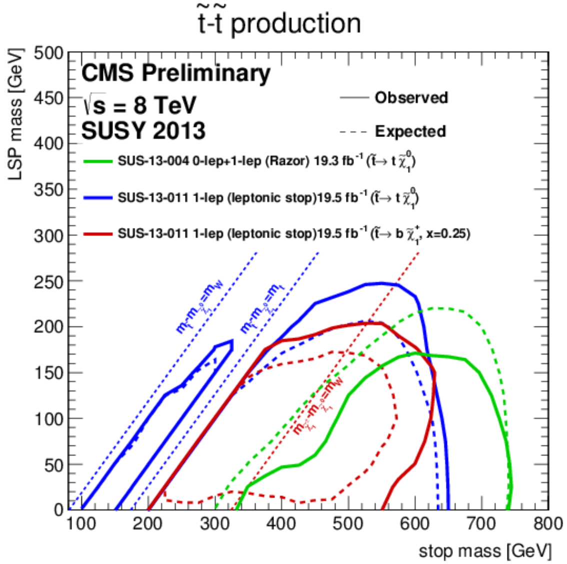
(not only strong but also electroweak)

– squarks and gluinos up to a few TeV,

– chargino/neutralino/sleptons to 1 TeV,

– LSP/DM neutralino upto few 100 GeV.

example of CMS reach in $\tilde{t}/\chi_1^0$ space ⇒



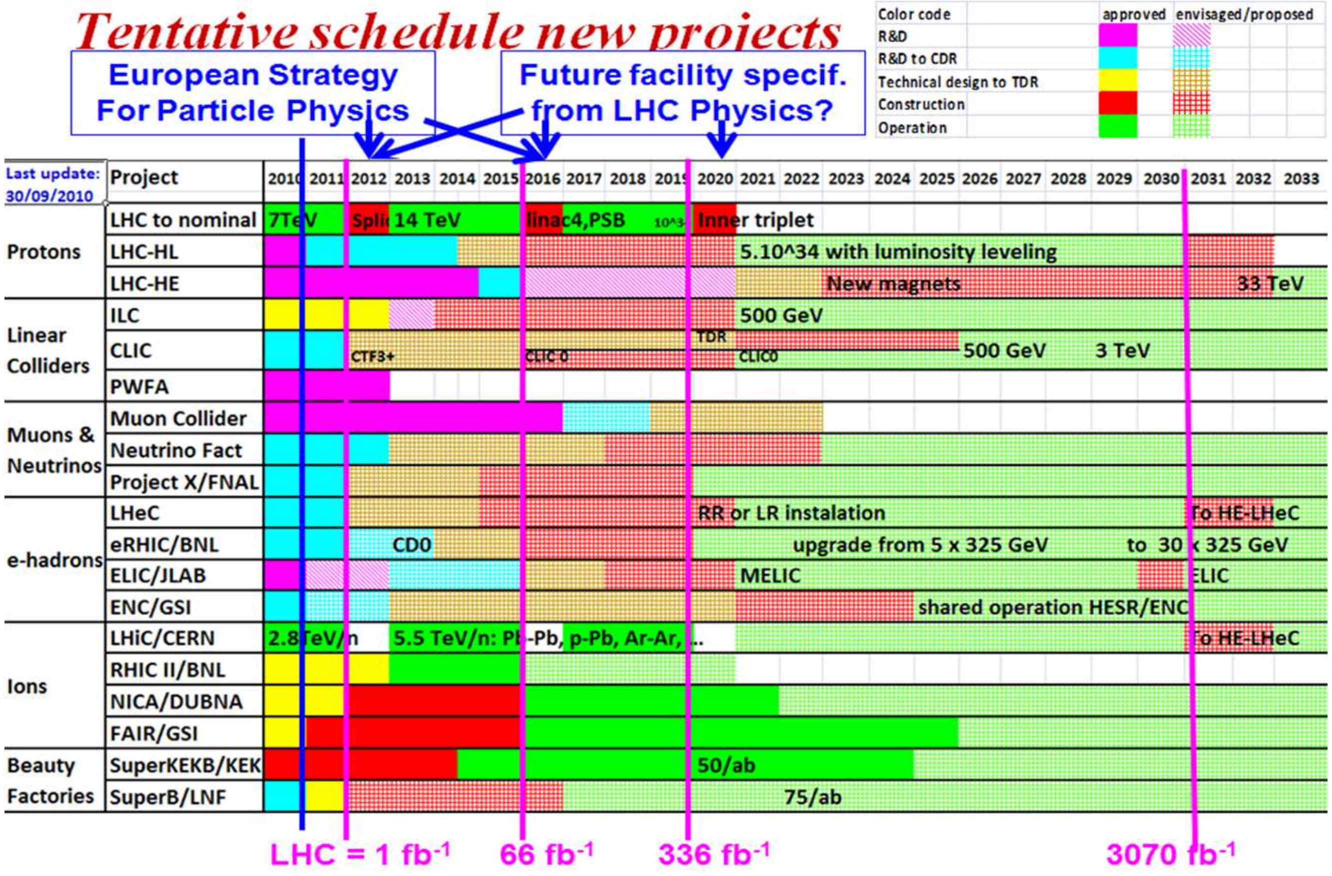
3) Search for any new particle: new $\mathrm{f}, \mathrm{Z'}, \mathrm{V_{KK}}$, etc... at TeV scale!

8. What next?

Hence, we need to continue search for New Physics and falsify the SM:

- **indirectly via high precision Higgs measurements (HL-LHC, ILC, ...),**
- **directly via heavy particle searches at high-energy (HE-LHC, CLIC),**

and we should plan/prepare/construct the new facilities already now!



Tentative schedule new projects

European Strategy For Particle Physics

Future facility specif. from LHC Physics?

Color code	approved	envisaged/proposed
R&D	🟪	▨
R&D to CDR	🟦	▨
Technical design to TDR	🟨	▨
Construction	🟥	▨
Operation	🟩	▨

Last update: 30/09/2010

	Project	2010 … 2033
	LHC to nominal	7TeV; Split; 14 TeV; linac4,PSB; 10^34; Inner triplet
Protons	LHC-HL	5.10^34 with luminosity leveling
	LHC-HE	New magnets; 33 TeV
Linear Colliders	ILC	500 GeV
	CLIC	CTF3+; CLIC 0; TDR; CLIC0; 500 GeV; 3 TeV
	PWFA	
Muons & Neutrinos	Muon Collider	
	Neutrino Fact	
	Project X/FNAL	
e-hadrons	LHeC	RR or LR instalation; To HE-LHeC
	eRHIC/BNL	CD0; upgrade from 5 x 325 GeV to 30 x 325 GeV
	ELIC/JLAB	MELIC; ELIC
	ENC/GSI	shared operation HESR/ENC
Ions	LHiC/CERN	2.8TeV/n; 5.5 TeV/n: Pb-Pb, p-Pb, Ar-Ar, ...; To HE-LHeC
	RHIC II/BNL	
	NICA/DUBNA	
	FAIR/GSI	
Beauty Factories	SuperKEKB/KEK	50/ab
	SuperB/LNF	75/ab

LHC = 1 fb^{-1} 66 fb^{-1} 336 fb^{-1} 3070 fb^{-1}

8. What next?

The end of the story is not yet told!

“Now, this is not the end.
It is not even the beginning to the end.
But it is perhaps the end of the beginning.”

Sir Winston Churchill, November 1942
(after the battle of El-Alamein, Egypt...).

We hope that at the end we finally understand the EWSB mechanism. But there is a long way until then, and there might be many surprises.

We should keep going!