HIGGS PHYSICS

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1. The Standard Model: brief introduction

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

- **a relativistic quantum field theory,**
- **based on local gauge symmetry: invariance under symmetry group,**
- **more or less a carbon–copy of QED, the theory of electromagnetism.**

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

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

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

The Lagrangian density is invariant under above field transformations

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

field strength $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ **and cov. derivative** $D_\mu = \partial_\mu - ieA_\mu$

Very simple and extremely successful theory!

– minimal coupling: the interactions/couplings uniquely determined,

– renormalizable, perturbative, unitary (predictive), very well tested...

1. The Standard Model: brief introduction

The SM is based on the local gauge symmetry group

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

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

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

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

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

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

The Lagrangian of the theory is given by:

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

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

The interactions/couplings are then uniquely determined:

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

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

1. The Standard Model: brief introduction

• $\mathrm{SU(2)_L \times U(1)_Y}$ **describes the electroweak 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: $\mu, \nu_\mu, \mathrm{c}, \mathrm{s};\ \tau, \nu_\tau, \mathrm{t}, \mathrm{b}$**.**

There is no ν_{R} **(and therefore neutrinos are and stay exactly massless)**

– mediated by the $\mathrm{W}_\mu^{\mathbf{i}}$ **(isospin) and** B_μ **(hypercharge) gauge bosons**

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

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

Lagrangian simple: with fields strengths and covariant derivatives

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

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

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

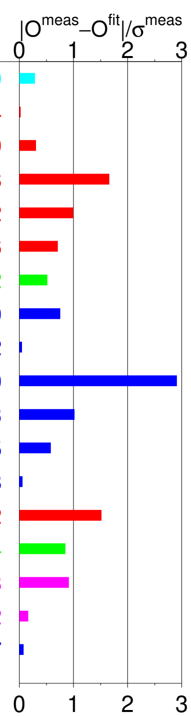
1. The Standard Model: brief introduction

⇒ **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 boson properties**
- **measurement & running of α_s**

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01646
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1039
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0743
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1482
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.378
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.27

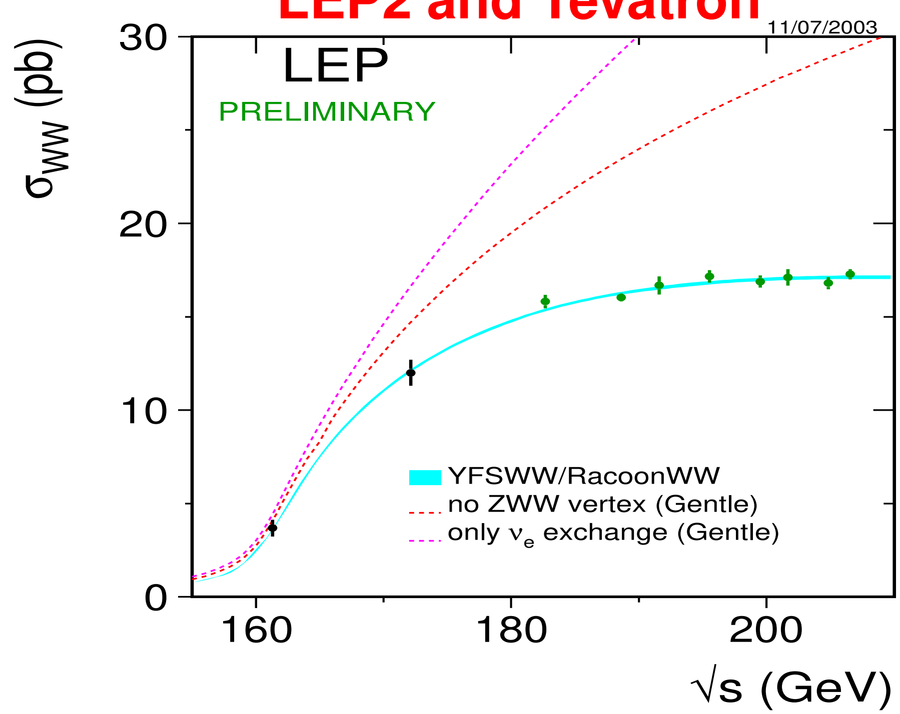


July 2011

LEP1, SLC, LEP2, Tevatron

- **Gauge structure of the SM**
- **Properties of the W bosons**

LEP2 and Tevatron



- **Physics of top&bottom quarks, QCD**

Tevatron, HERA and B factories

1. The Standard Model: brief introduction

There is a big problem with picture: fermions and W/Z are massive!

However, 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):**

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

again this mass term is non–invariant under SU(2)xU(1) gauge symmetry.

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

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

2. EWSB in the SM

In SM, gauge boson and fermion masses come from spontaneous EWSB:

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

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

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

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

$\mu^2 < 0$: Φ **develops a vev:**

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

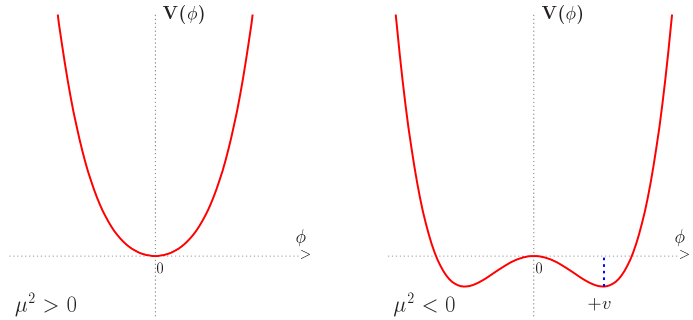
$$\text{with vev} \equiv v = (-\mu^2/\lambda)^{\frac{1}{2}}$$

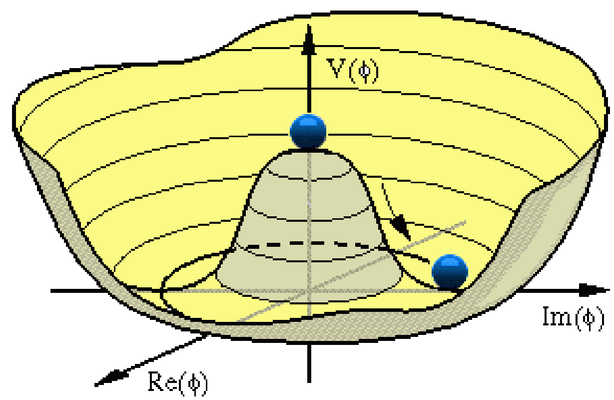
– symmetric minimum: instable

– true vacuum: degenerate

$\Rightarrow$ **to obtain the physical states,**

write $\mathcal{L}_S$ **with the true vacuum:**





2. EWSB in SM: mass generation

- Write Φ in terms of four fields $\theta_{1,2,3}(x)$ and H(x) at 1st order:

$$\Phi(x) = e^{i\theta_a(x)\tau^a(x)/v} \frac{1}{\sqrt{2}}\binom{0}{v+H(x)} \simeq \frac{1}{\sqrt{2}}\binom{\theta_2+i\theta_1}{v+H-i\theta_3}$$

- Make a gauge transformation on Φ to go to the unitary gauge:

$$\Phi(x) \to e^{-i\theta_a(x)\tau^a(x)}\, \Phi(x) = \frac{1}{\sqrt{2}}\binom{0}{v+H(x)}$$

- Then fully develop the term $|D_\mu\Phi)|^2$ of the Lagrangian $\mathcal{L}_S$:

$$|D_\mu\Phi)|^2 = \left|\left(\partial_\mu - ig_2\frac{\tau_a}{2}W_\mu^a - i\frac{g_1}{2}B_\mu\right)\Phi\right|^2$$

$$= \frac{1}{2}\left|\begin{pmatrix} \partial_\mu - \frac{i}{2}(g_2 W_\mu^3 + g_1 B_\mu) & -\frac{ig_2}{2}(W_\mu^1 - iW_\mu^2) \\ -\frac{ig_2}{2}(W_\mu^1 + iW_\mu^2) & \partial_\mu + \frac{i}{2}(g_2 W_\mu^3 - g_1 B_\mu) \end{pmatrix} \binom{0}{v+H}\right|^2$$

$$= \frac{1}{2}(\partial_\mu H)^2 + \frac{1}{8}g_2^2(v+H)^2|W_\mu^1 + iW_\mu^2|^2 + \frac{1}{8}(v+H)^2|g_2 W_\mu^3 - g_1 B_\mu|^2$$

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

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

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

2. EWSB in SM: mass generation

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

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

$\Rightarrow$ 3 degrees of freedom for $W_L^{\pm}, Z_L$ and thus $M_{W^\pm}, M_Z$:

$$M_W = \frac{1}{2} v g_2 \,,\ M_Z = \frac{1}{2} v \sqrt{g_2^2 + g_1^2} \,,\ M_A = 0 \,,$$

with the value of the vev given by: $v = 1/(\sqrt{2} G_F)^{1/2} \sim 246\ \mathrm{GeV}$.

$\Rightarrow$ The photon stays massless, $U(1)_{QED}$ is preserved.

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

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

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

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

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

What about the residual degree of freedom?

2. EWSB in SM: the Higgs boson

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

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

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

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

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

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

The Higgs boson mass is given by: $M_H^2 = 2\lambda v^2 = -2\mu^2$.

The Higgs triple and quartic self–interaction vertices are:

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

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

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

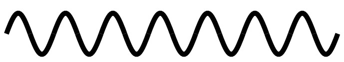
$$\mathcal{L}_{M_V} \sim M_V^2 (1 + H/v)^2 \ , \ \mathcal{L}_{m_f} \sim -m_f(1 + H/v)$$

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

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

2. EWSB in SM: W/Z/H at high energies

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



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

$\zeta = \infty$: **Landau gauge**

$\zeta = 1$: **'t Hooft-Feynman**

$\omega^\pm, \omega^0$:

$\longrightarrow q$ $\quad \frac{-i}{q^2 - \zeta M_V^2 + i\epsilon}$

- **In unitary gauge, Goldstones do not propagate and gauge bosons have usual propagators of massive spin–1 particles (old IVB theory).**
- **At very high energies, $\mathrm{s} \gg \mathrm{M_V^2}$, an approximation is $\mathrm{M_V} \sim 0$. The $\mathrm{V_L}$ components of V can be replaced by the Goldstones, $\mathrm{V_L} \to \mathrm{w}$.**
- **In fact, the electroweak equivalence theorem tells that at high energies, massive vector bosons are equivalent to Goldstones. In VV scattering e.g.:**

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

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

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

2. EWSB in the SM

Simplest SM extension: add one scalar ϕ that develops a vev v_ϕ; it has:

$$\mathrm{V}(\Phi,\phi) = \lambda(\Phi^\dagger\Phi)^2 + \mu^2\Phi^\dagger\Phi + \lambda_{\mathrm{HH'}}\Phi^\dagger\Phi\phi^2 + \lambda_\phi\phi^4 + \mu_\phi^2\phi^2$$

after EWSB ($\mu_\phi^2 < 0$), one has two Higgs bosons H and H' which mix

$$\binom{\mathrm{H}}{\mathrm{H'}} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} = \binom{\mathrm{Re}\Phi^0}{\mathrm{Re}\phi^0} \ \text{with} \tan 2\theta = \frac{\lambda_{\mathrm{HH'}}\mathrm{v}\mathrm{v}_\phi}{\lambda_\phi \mathrm{v}_\phi^2 - \lambda \mathrm{v}}$$

The masses of the two physical states read (H is the SM-like boson) :

$$\mathrm{M}^2_{\mathrm{H/H'}} = (\lambda\mathrm{v} + \lambda_\phi \mathrm{v}_\phi) \mp |\lambda \mathrm{v}^2 - \lambda_\phi \mathrm{v}_\phi^2|\sqrt{1+\tan^2 2\theta}$$

The model has 3 parameters (on top of v and $\mathrm{M_H}$): $\mathrm{M_{H'}}, \lambda_{\mathrm{HH'}}, \sin\theta$ with

$$\lambda = \frac{\mathrm{M_H^2}}{2\mathrm{v}^2} + \frac{\Delta \mathrm{M}^2_{\mathrm{H'H}} \mathrm{s}_\theta^2}{2\mathrm{v}^2}, \lambda_\phi = \frac{2\lambda^2_{\mathrm{HH'}}\mathrm{v}^2}{\mathrm{s}^2_{2\theta}\Delta \mathrm{M}^2_{\mathrm{H'H}}}\left(\frac{\mathrm{M_H^2}}{\Delta \mathrm{M}^2_{\mathrm{H'H}}} - \mathrm{s}_\theta^2\right), \mathrm{v}_\phi = -\frac{\Delta \mathrm{M}^2_{\mathrm{H'H}}\mathrm{s}_{2\theta}}{2\lambda_{\mathrm{HH'}}\mathrm{v}}$$

H' and H will share the SM Higgs couplings to fermions and gauge bosons:

$$\mathcal{L}^{\mathrm{HH'}}_{\mathrm{SM}} = (\mathrm{H}\mathrm{c}_\theta - \mathrm{H'}\mathrm{s}_\theta)\left[\frac{2\mathrm{M_W^2}}{\mathrm{v}}\mathrm{W}^+_\mu \mathrm{W}^{\mu -} + \frac{\mathrm{M_Z^2}}{\mathrm{v}}\mathrm{Z}^\mu \mathrm{Z}_\mu - \sum_{\mathrm{f}} \frac{\mathrm{m_f}}{\mathrm{v}}\bar{\mathrm{f}}\mathrm{f}\right]$$

The trilinear couplings are slightly more complicated than in the SM; ex:

$$\mathcal{L}^{\mathrm{HH'}}_{\mathrm{scal}} = -\frac{\mathrm{v}}{2}\left[\kappa_{\mathrm{HHH}}\mathrm{H}^3 + \kappa_{\mathrm{HHH'}}\mathrm{s}_\theta \mathrm{H}^2\mathrm{H'} + \kappa_{\mathrm{HH'H'}}\mathrm{c}_\theta \mathrm{HH'}^2 + \kappa_{\mathrm{H'H'H'}}\mathrm{H'}^3\right]$$

$$\kappa_{\mathrm{HHH}} = \frac{\mathrm{M_H^2}}{\mathrm{v}^2\mathrm{c}_\theta}\left(\mathrm{c}_\theta^4 - \mathrm{s}_\theta^2 \frac{\lambda_{\mathrm{HH'}}\mathrm{v}^2}{\Delta \mathrm{M}^2_{\mathrm{HH'}}}\right), \ \kappa_{\mathrm{HHH'}} = \frac{2\mathrm{M_H^2}+\mathrm{M^2_{H'}}}{\mathrm{v}^2}\left(\mathrm{c}_\theta^2 + \frac{\lambda_{\mathrm{HH'}}\mathrm{v}^2}{\Delta \mathrm{M}^2}\right)$$

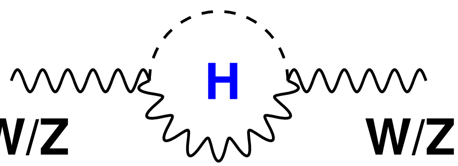
3. Constraints on M_H

Before LHC, only unknown SM parameter was M_H; but some information.

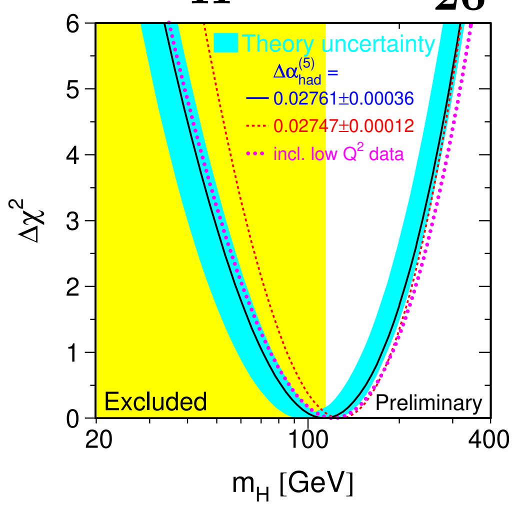
First, there were constraints from pre–LHC experiments: LEP, Tevatron...

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

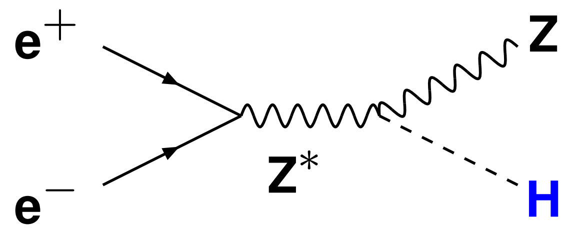


$M_H \lesssim 160$ GeV at 95% CL

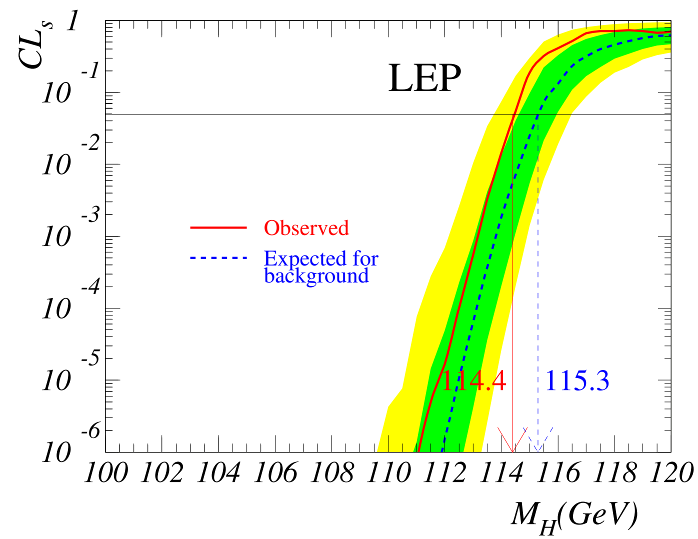
($M_H \lesssim 126$ GeV at 68% CL!)

Direct searches at colliders:

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



$M_H > 114.4$ GeV @95%CL

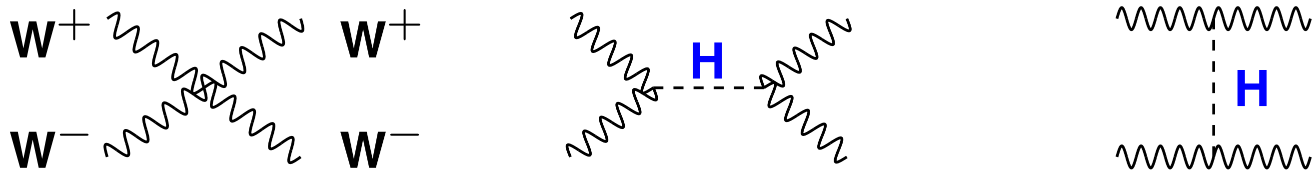


Tevatron $M_H \neq 160-175$ GeV

(3σ evidence a few days before..)

3. Constraints on M_H: perturbative unitarity

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



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

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

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

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

For unitarity to be fullfilled, 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: $a_0 \xrightarrow{s \ll M_H^2} -\frac{s}{32\pi v^2}$

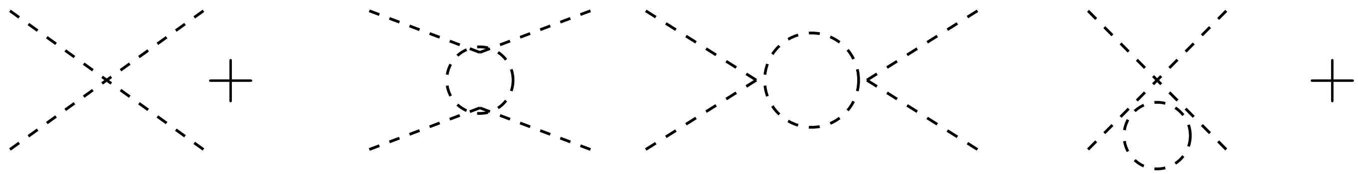
$$\text{unitarity} \Rightarrow \sqrt{s} \lesssim 1.7\ \text{TeV} \ \ (\sqrt{s} \lesssim 1.2\ \text{TeV})$$

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

3. Constraints on M_H: triviality

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

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



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

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

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

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

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

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

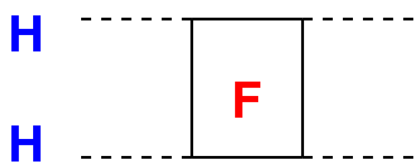
If $\Lambda_C = M_P,\ \lambda \lesssim 4\pi \Rightarrow M_H \lesssim 180$ GeV

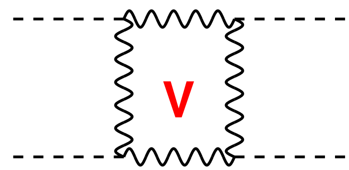
(comparable to exp. limit if SM extrapolated to GUT/Planck scales)

3. Constraints on M_H: vacuum stability

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

(contributions dominant (over that of H itself) at low M_H values)





The RGE evolution of the coupling at one–loop is given by

$$\lambda(Q^2) = \lambda(v^2) + \frac{1}{16\pi^2}\left[-12\frac{m_t^4}{v^4} + \frac{3}{16}\left(2g_2^4 + (g_2^2+g_1^2)^2\right)\right]\log\frac{Q^2}{v^2}$$

If λ is small (H is light), top loops might lead to $\lambda(0) < \lambda(v)$:

v is not the minimum of the potential 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 before LEP2...)

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

3. Constraints on M_H: triviality+stability

Combine the two constraints and include all possible effects:

– corrections at two loops

– theoretical+exp. errors

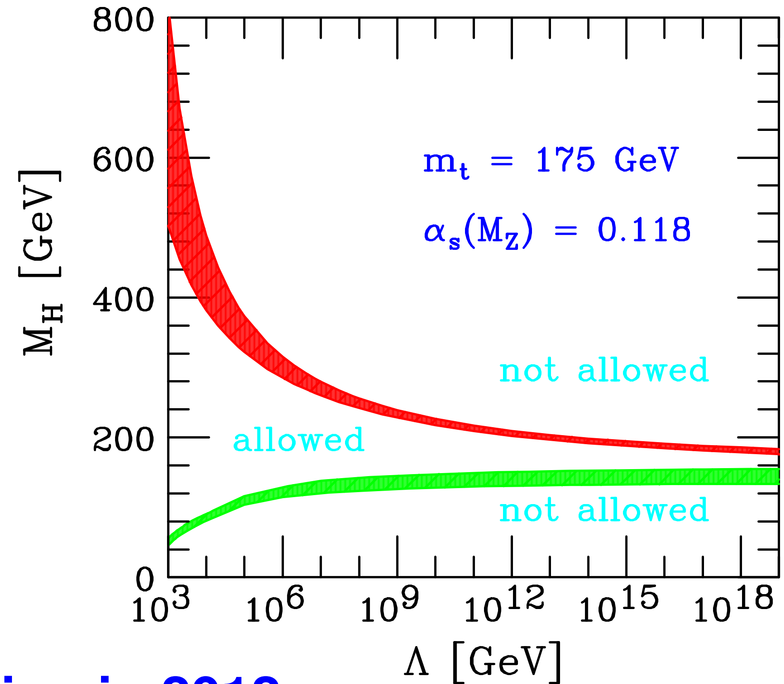
– other refinements $\cdots$

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

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

Cabibbo, Maiani, Parisi, Petronzio

Hambye, Riesselmann



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

Degrassi et al., Berzukov et al.

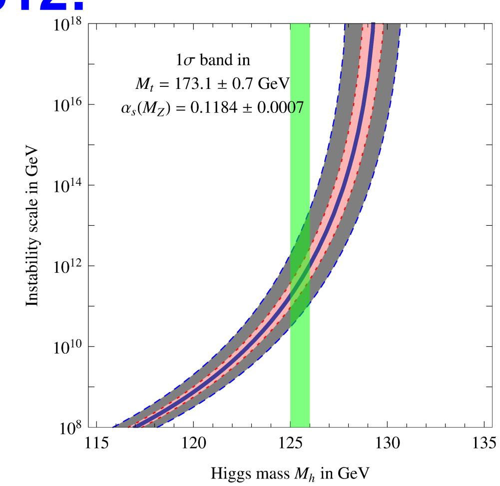
At 2–loop accuracy for m_t^{pole}=173.1 GeV:

fully stable vacuum if $M_H \gtrsim 129$ GeV...

but vacuum metastable for M_H below.

metastability OK: the vacuum is unstable

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

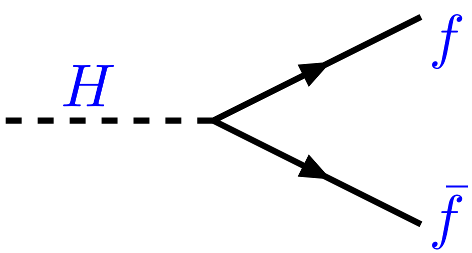


4. Higgs decays

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

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

Higgs decays into fermions:



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

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

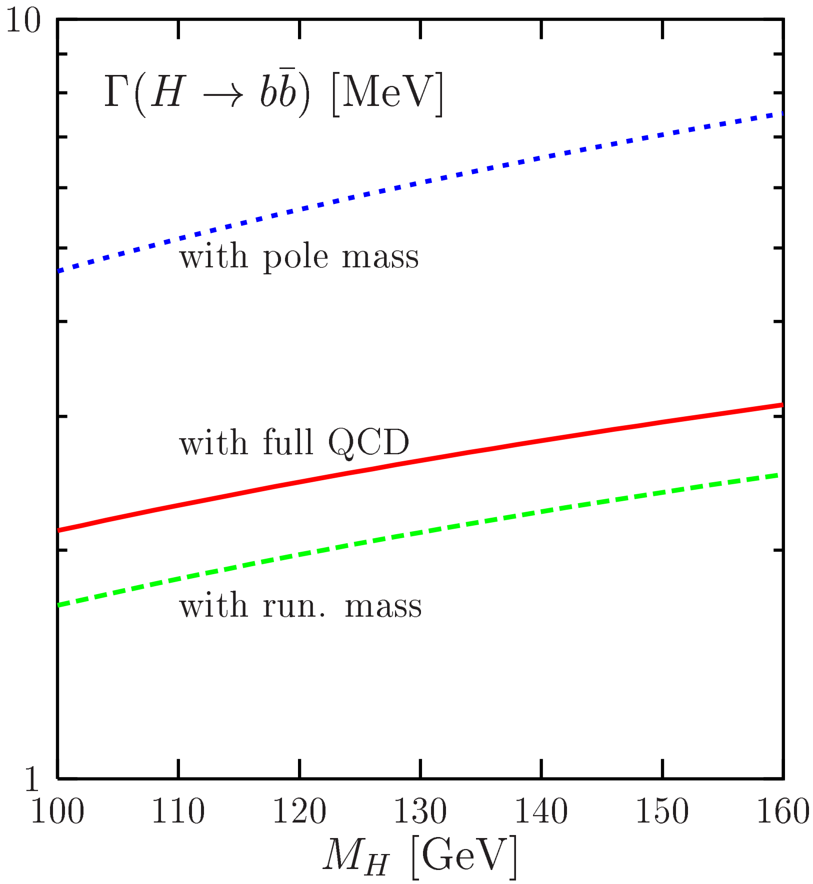
$$N_c = \text{color number}$$

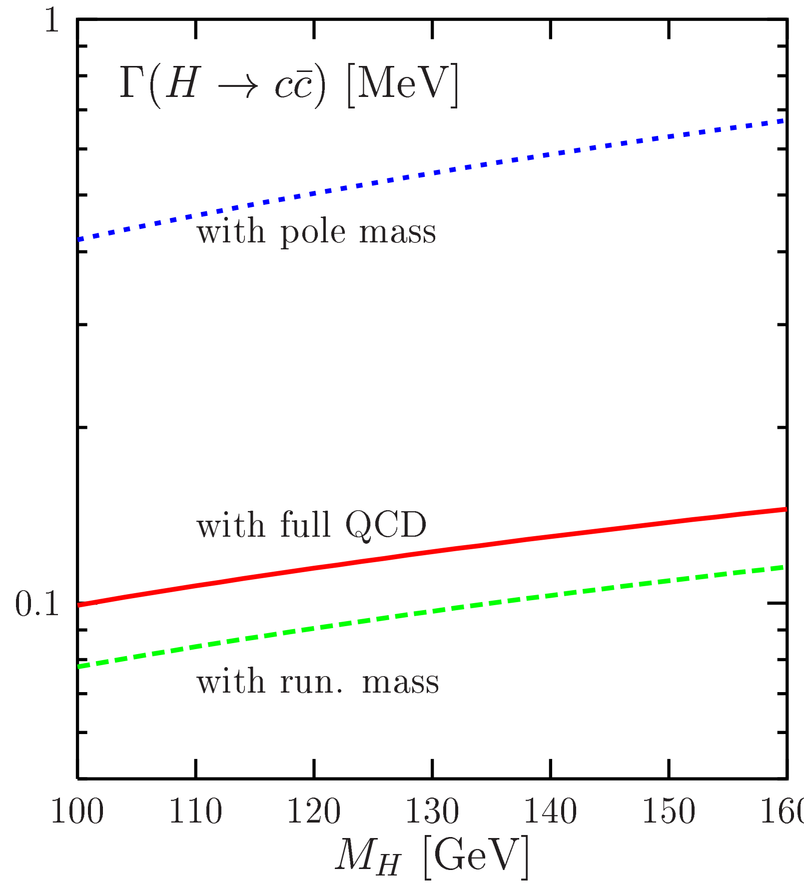
- Only $b\bar{b}, c\bar{c}, \tau^+\tau^-, \mu^+\mu^-$ for $M_H < 350$ GeV, also $t\bar{t}$ beyond.
- $\Gamma \propto \beta^3$: H is CP–even scalar particle ($\propto \beta$ for pseudoscalar H).
- Decay width grows as M_H: moderate growth....
- QCD RC: $\Gamma \propto \Gamma_0[1 - \frac{\alpha_s}{\pi}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

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

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

4. Higgs decays: QCD corrections

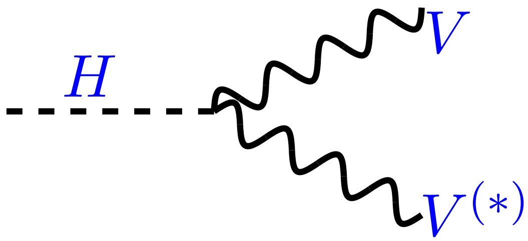




Q	m_Q	$\overline{m}_Q(m_Q)$	$\overline{m}_Q(100\ \mathrm{GeV})$
c	1.64 GeV	1.23 GeV	0.63 GeV
b	4.88 GeV	4.25 GeV	2.95 GeV

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

4. Higgs decays: decays into gauge bosons



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

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

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

• **For a very heavy Higgs boson:**

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

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

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

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

• **For a light Higgs boson:**

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

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

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

4. Higgs decays: decays into gauge bosons

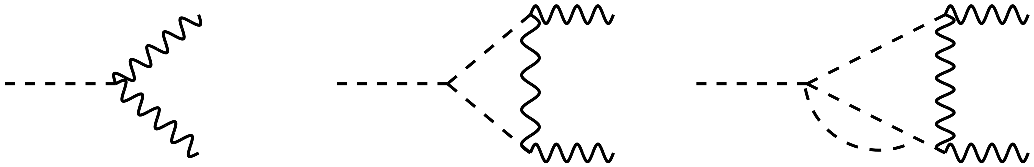
Electroweak radiative corrections to $H \to VV$:

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:

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

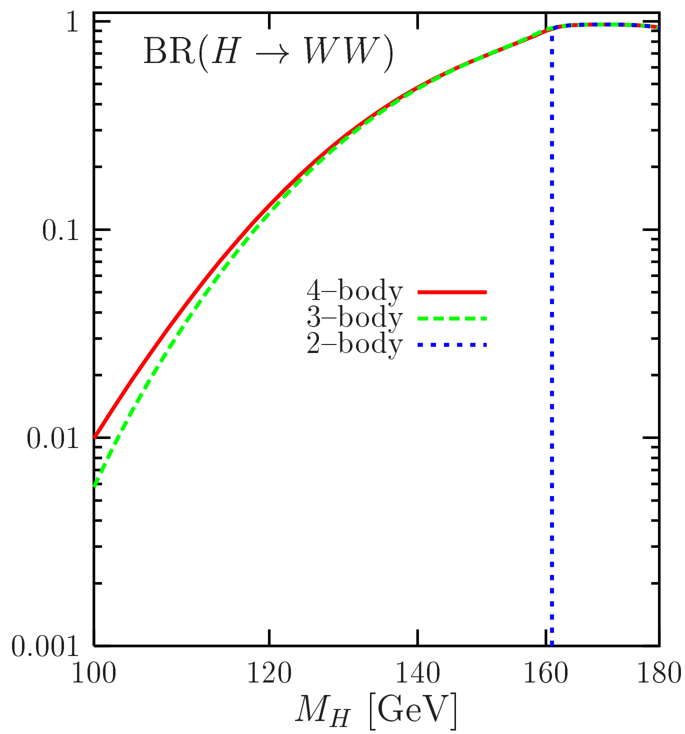
4. Higgs decays: decays into gauge bosons

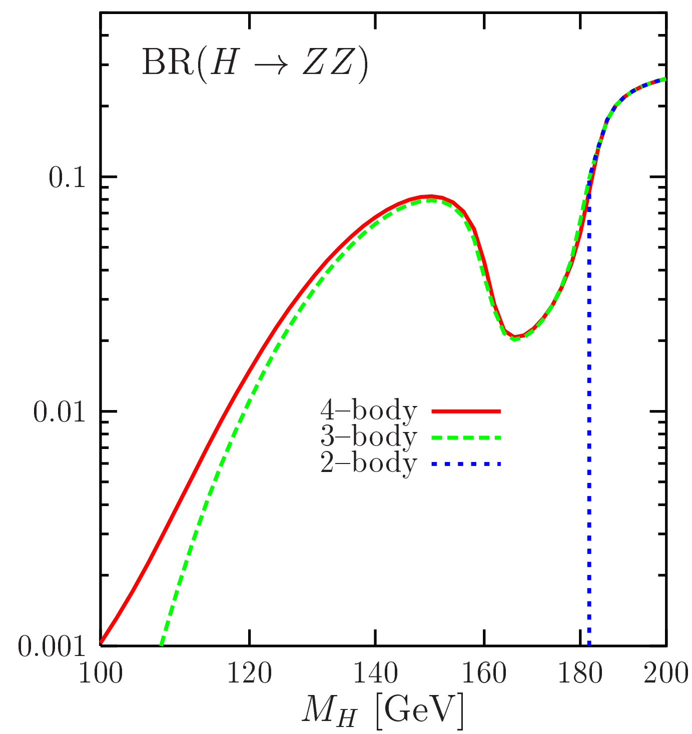
general 2+3+4 body decay calculation of $H \to V^* V^*$:

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

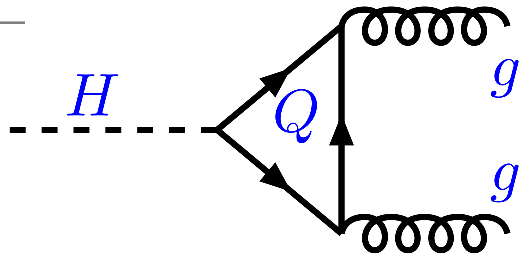
$\lambda(x, y; z) = (1 - x/z - y/z)^2 - 4xy/z^2$ with $\delta_{W/Z} = 2/1$ and

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





4. Higgs decays: decays into gluons



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

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

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

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

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

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

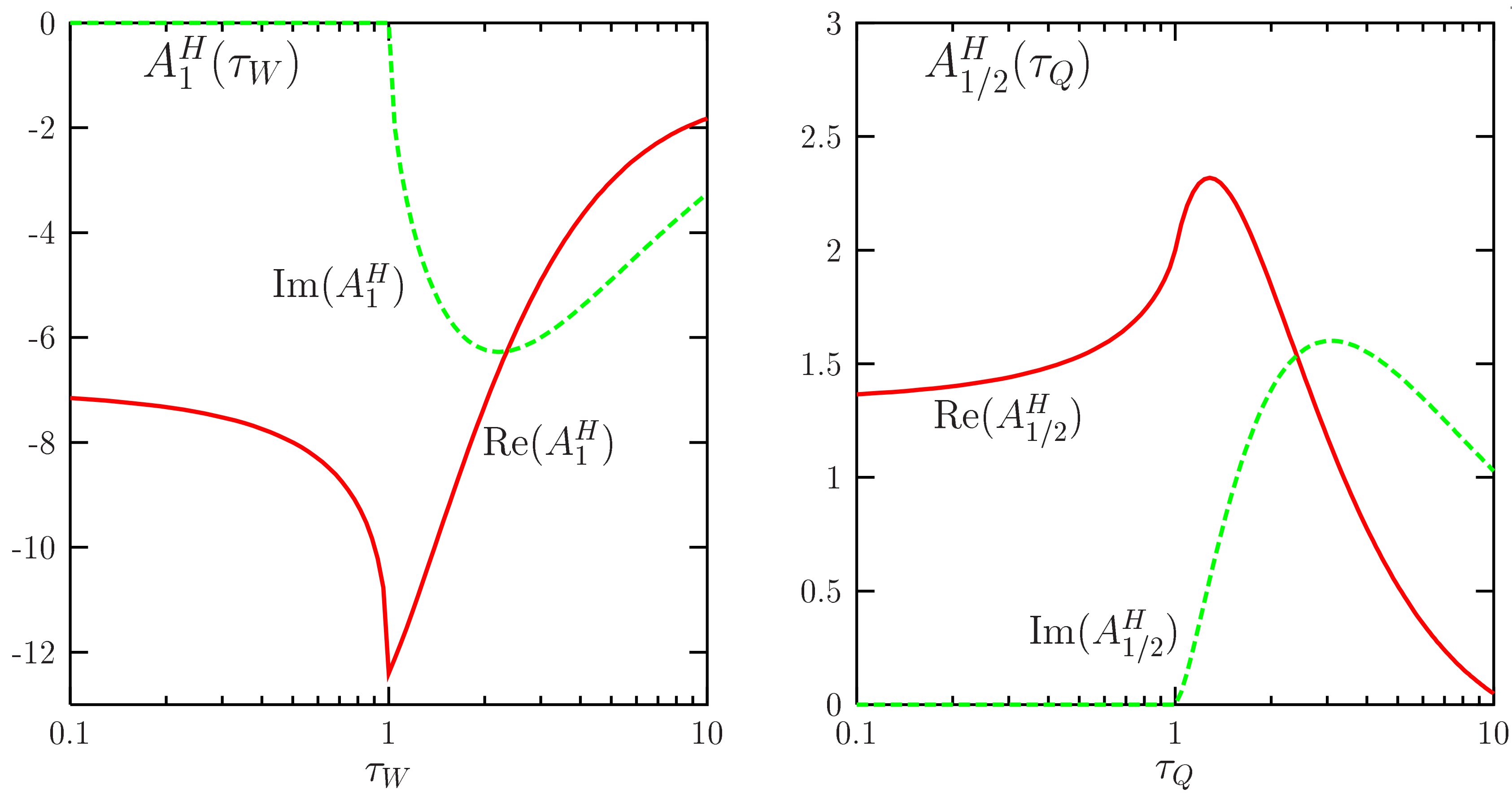
Good approximation in decay: include only t–loop with $m_Q \to \infty$. But:

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

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

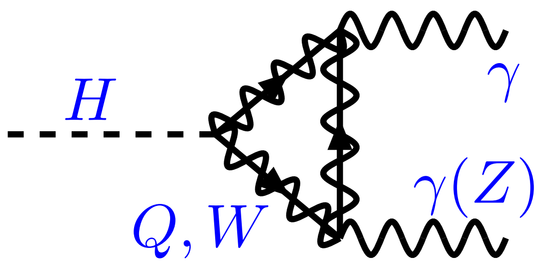
- Reverse process $gg \to H$ very important for Higgs production in pp!

4. Higgs decays: loop form factors



W and fermion amplitudes in $\mathrm{H} \to \gamma\gamma$ as function of $\tau_\mathrm{i} = \mathrm{M_H^2}/4\mathrm{M_i^2}$.
Trick for an easy calculation: low energy theorem for $\mathrm{M_H} \ll \mathrm{Mi}$:
replaces vertex calculation by easier two-point function (self-energy) one.

4. Higgs decays: decays into photons



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

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

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

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

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

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

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

4. Higgs decays: branching ratios

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

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

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

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

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

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

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

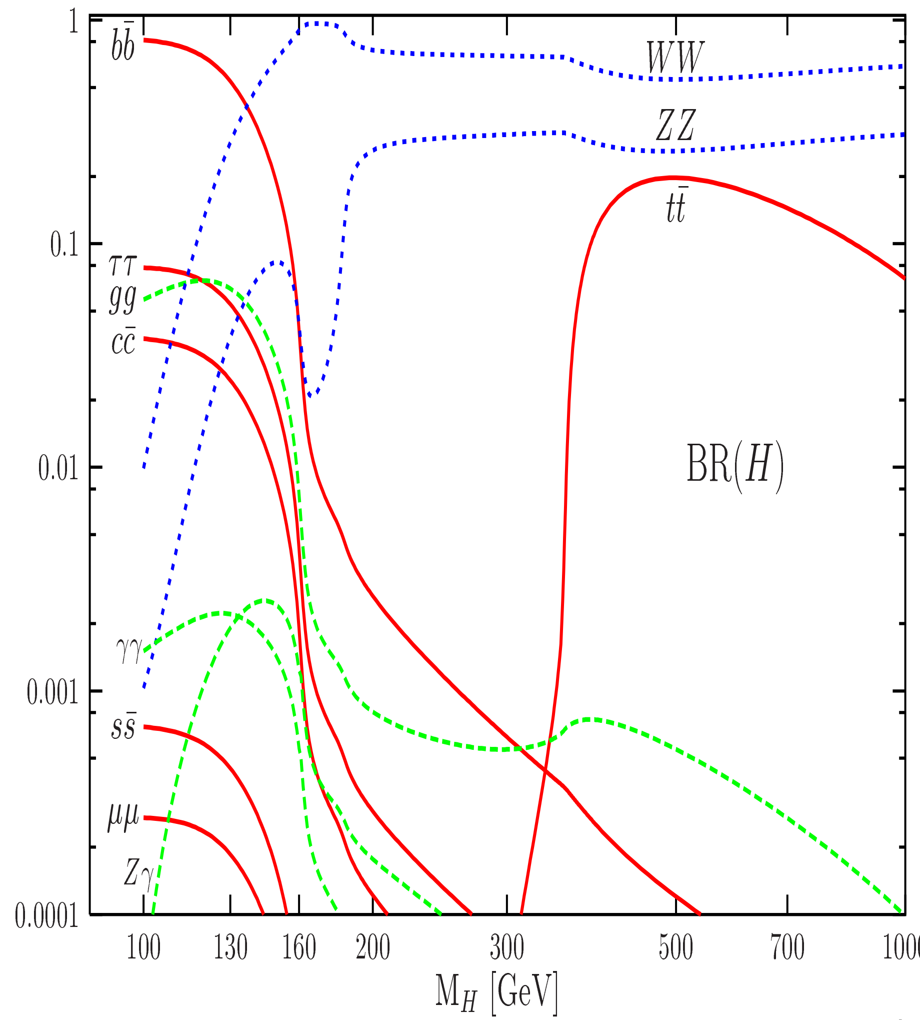
– $\mathrm{H \to WW, ZZ}$ **above (BR** $\to \frac{2}{3}, \frac{1}{3}$**)**

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

- **The Higgs total decay width:**

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

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



4. Higgs decays: total width

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

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

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

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

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

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

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

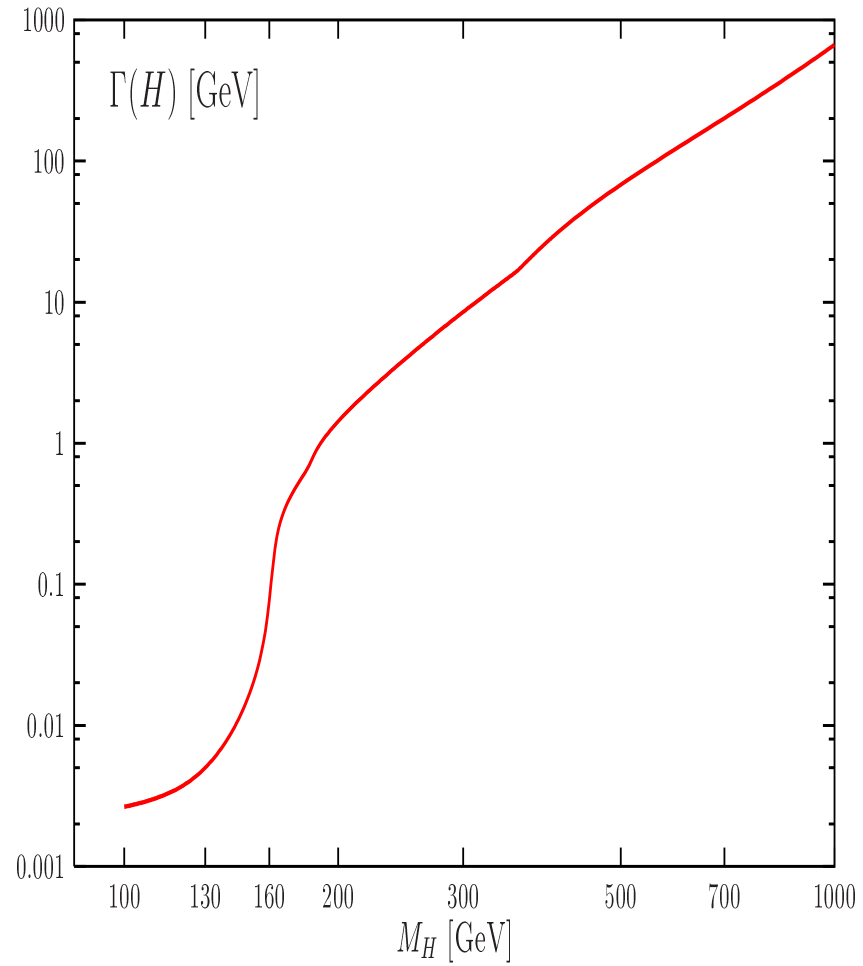
– $H \to WW, ZZ$ **above (BR** $\to \frac{2}{3}, \frac{1}{3}$**)**

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

- **The Higgs total decay width:**

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

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



4. Higgs decays: theory uncertainties

However: there are theoretical uncertainties....

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

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

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

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

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

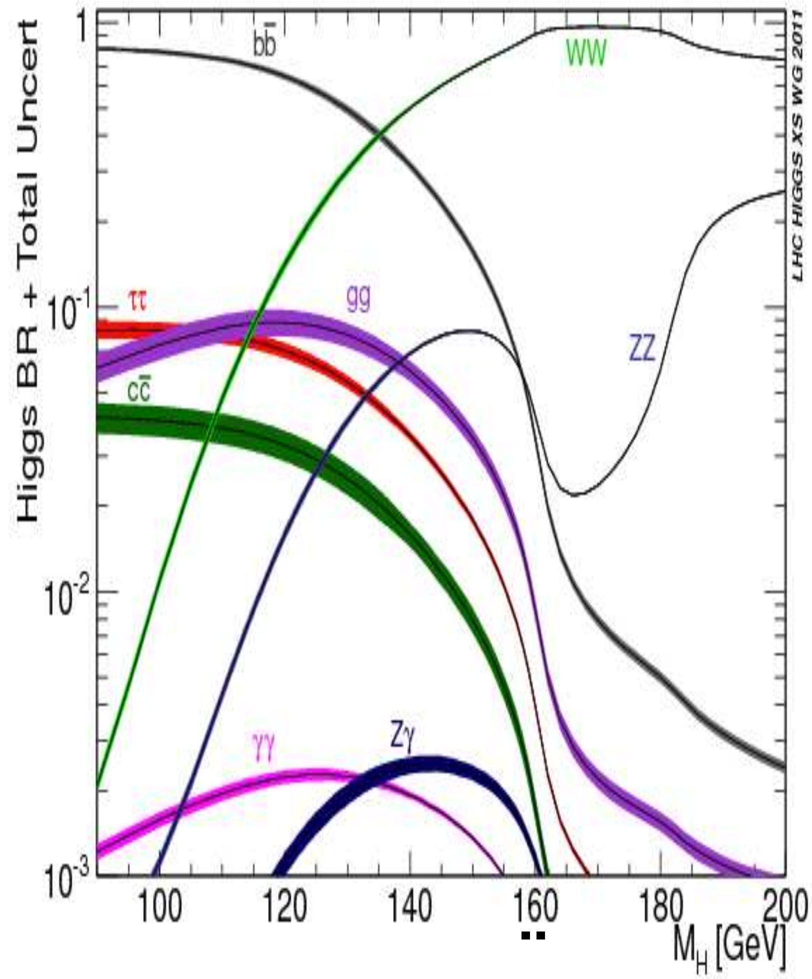
$\alpha_s(\mathrm{M_Z^2}) = 0.117 \pm 0.0014$ @NNLO

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

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

- **Scale and α_s errors in $\mathrm{H \to gg}$.**

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

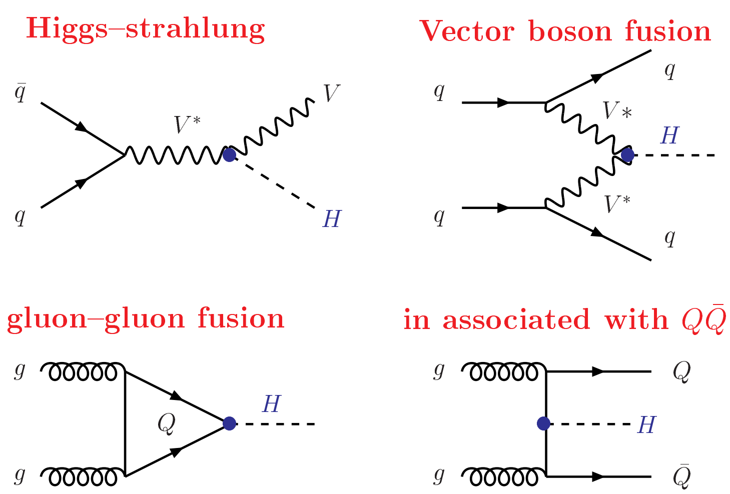


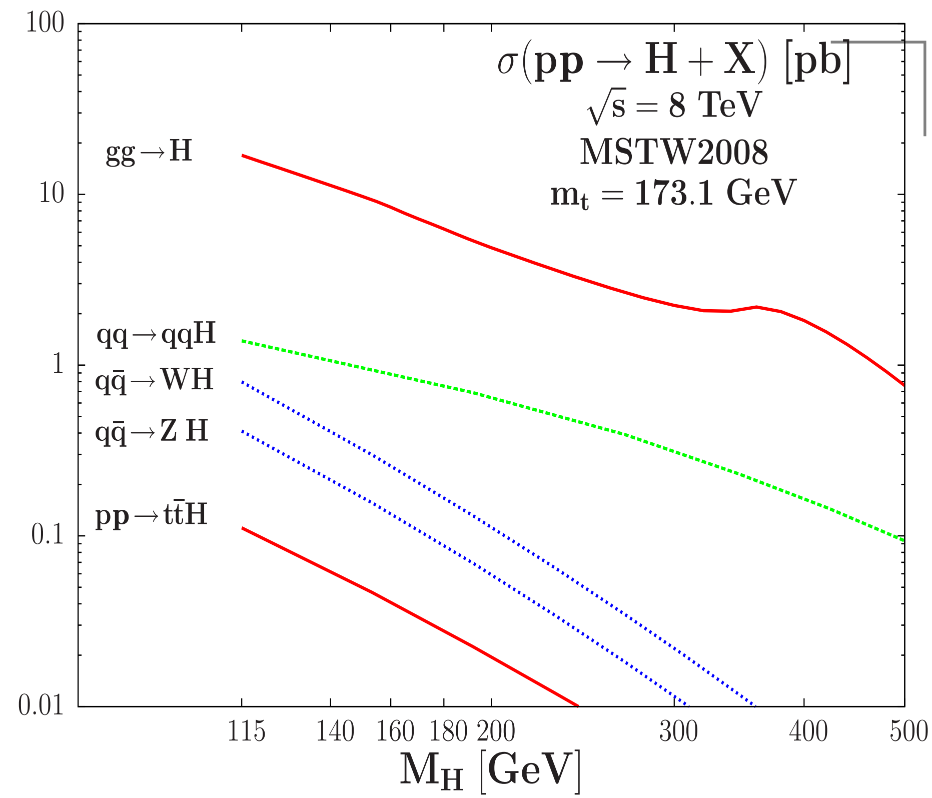
Include all individual items ⇒ small/moderate total uncertainty

esp. for $\mathrm{M_H}$ ≈120–150 GeV: a few % for $\mathrm{H \to b\bar{b}}$ and $\mathrm{H \to WW^*}$

5. SM Higgs at hadron colliders

Main Higgs production channels





Large production cross sections

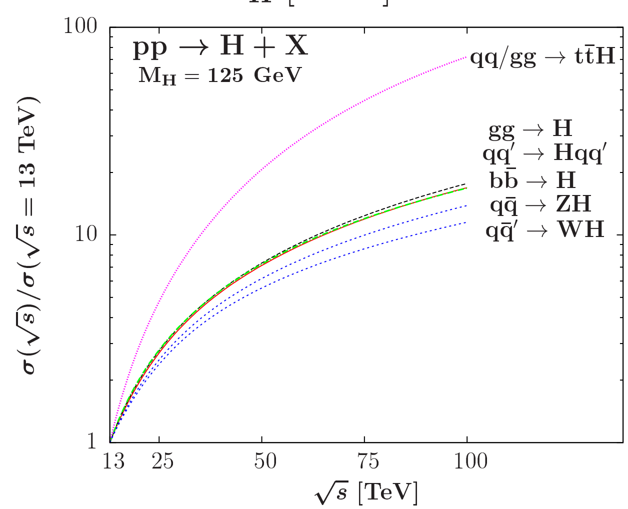
with gg→ H by far dominant process

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

$\Rightarrow \mathcal{O}(10^5)$ events @LHC

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

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



5. SM Higgs at hadron colliders: generalities

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

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

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

– trigger: get rid of uninteresting events...

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

– use specific kinematic features of Higgs

- **Combine # decay/production channels**

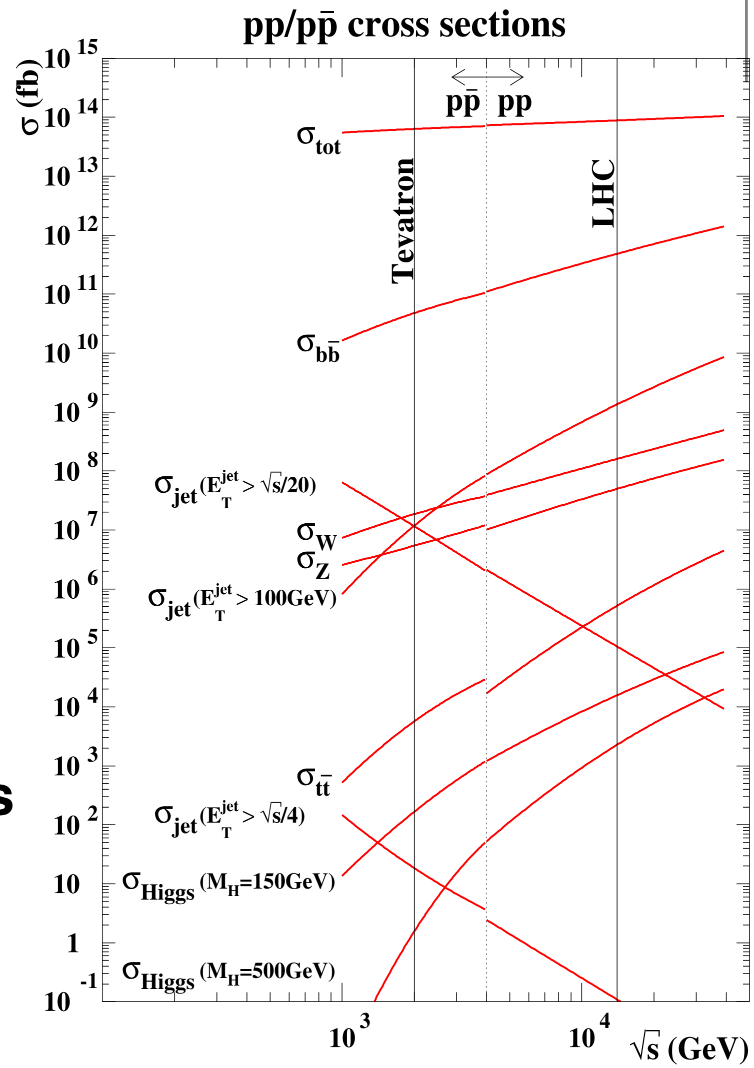
(and eventually several experiments...)

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

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

- **Gigantic experimental + theoretical efforts**

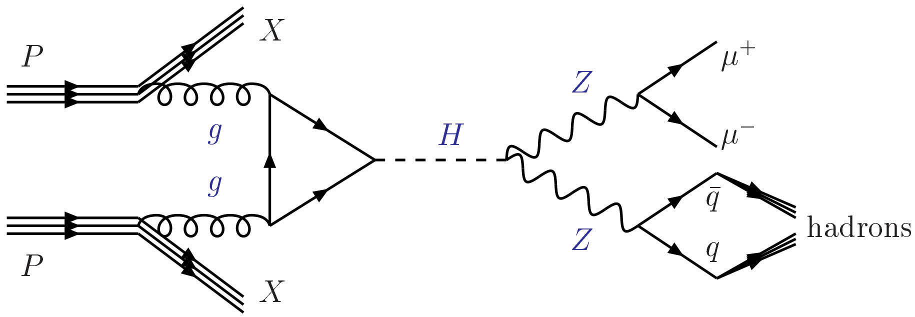
(more than 30 years of very hard work!)



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

5. SM Higgs at hadron colliders: generalities

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



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

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

Two ingredients: hard (σ, B) and soft processes (PDF, hadronisation).

But factorization theorem. Here we discuss production/decay process.

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

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

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

Convolute with gluon densities to obtain total hadronic cross section

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

5. SM Higgs at hadron colliders: generalities

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

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

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

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

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

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

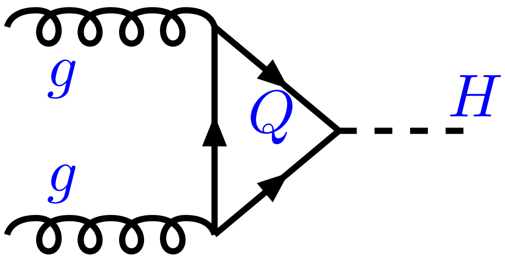
In fact, one has to do this for both the signal and background (unless directly measurable from data): the important quantity is $\sigma = \frac{N_S}{\sqrt{N_{bjg}}}$

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

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

5. SM Higgs production: gg fusion

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



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

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

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.**

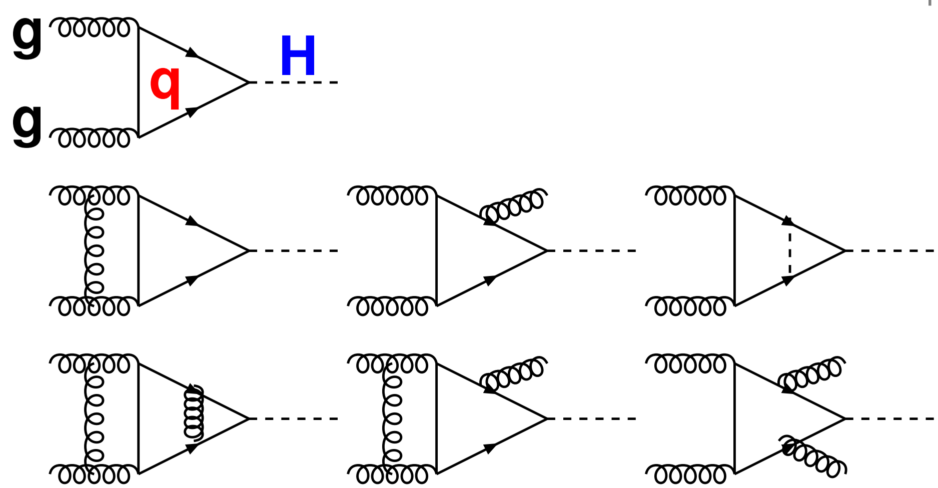
- **Very large QCD RC: the two– and three–loops have to be included.**
- **Also the Higgs** P_T **is zero at LO, must generated at NLO.**

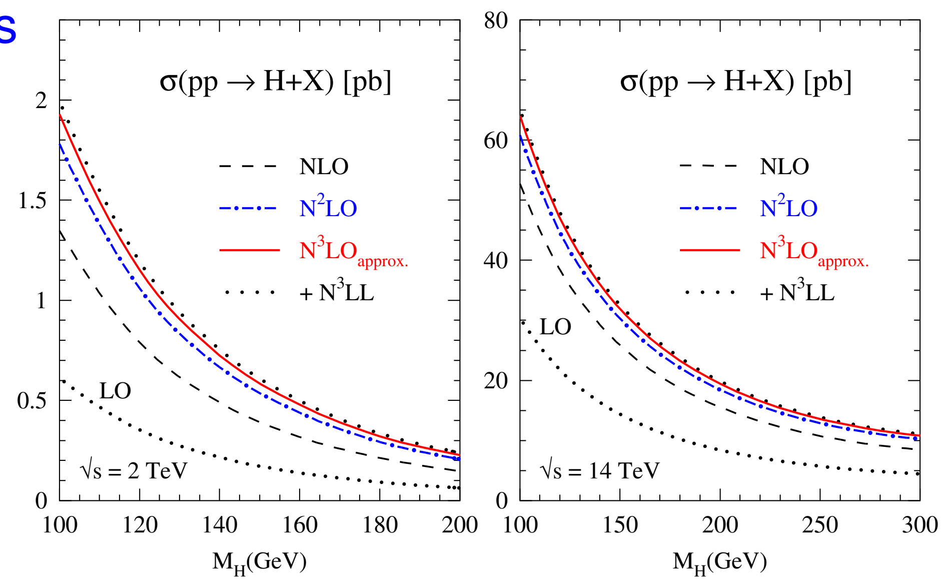
5. SM Higgs production: gg fusion

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 N^3LO[e]: $\approx +$few% (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: a few 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] Anastasiou et al.
[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.; Grazziniet; Nason...

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





Moch+Vogt

5. SM Higgs production: gg fusion

- **At NLO: corrections known exactly, i.e. for finite m_t and M_H:**

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

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

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

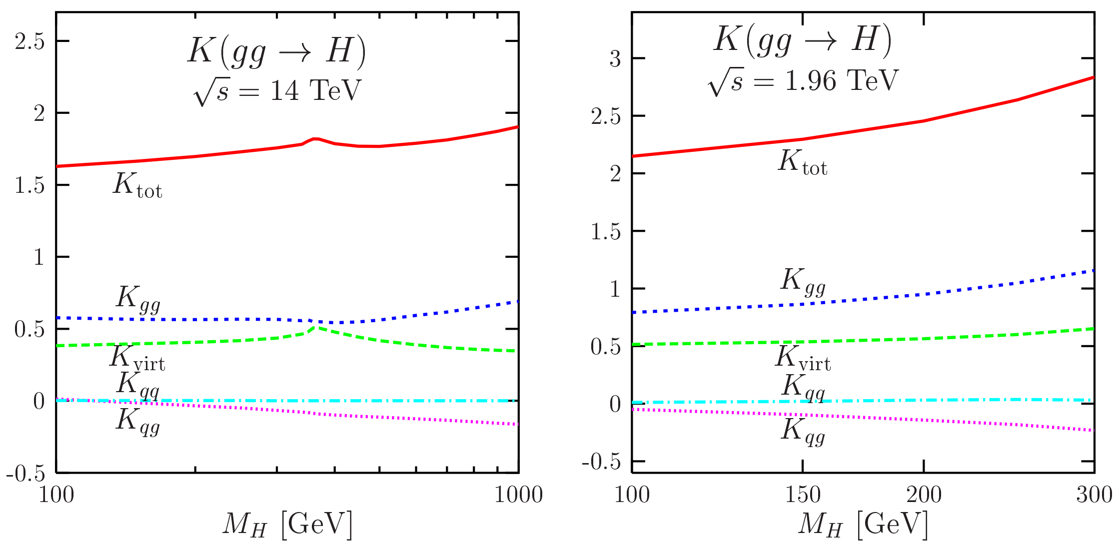
- **Corrections have been calculated in $m_t \to \infty$ limit beyond NLO.**

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

– Corrections at N^3L0 also available but small: $\approx$ a few % increase.

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

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



5. SM Higgs production: gg fusion

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

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

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

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

at lHC: $\mu_0 = \frac{1}{2}M_H, \kappa = 2 \Rightarrow \Delta_{\rm scale} \approx 5\%$

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

gluon PDF at high-x less data constrained
α_s uncertainty (WA, DIS?) affects $\sigma \propto \alpha_s^2$
$\Rightarrow$ some discrepancy between NNLO PDFs
PDF4LHC recommend: $\Delta_{\rm pdf} \approx 5\% @ {\rm LHC}$

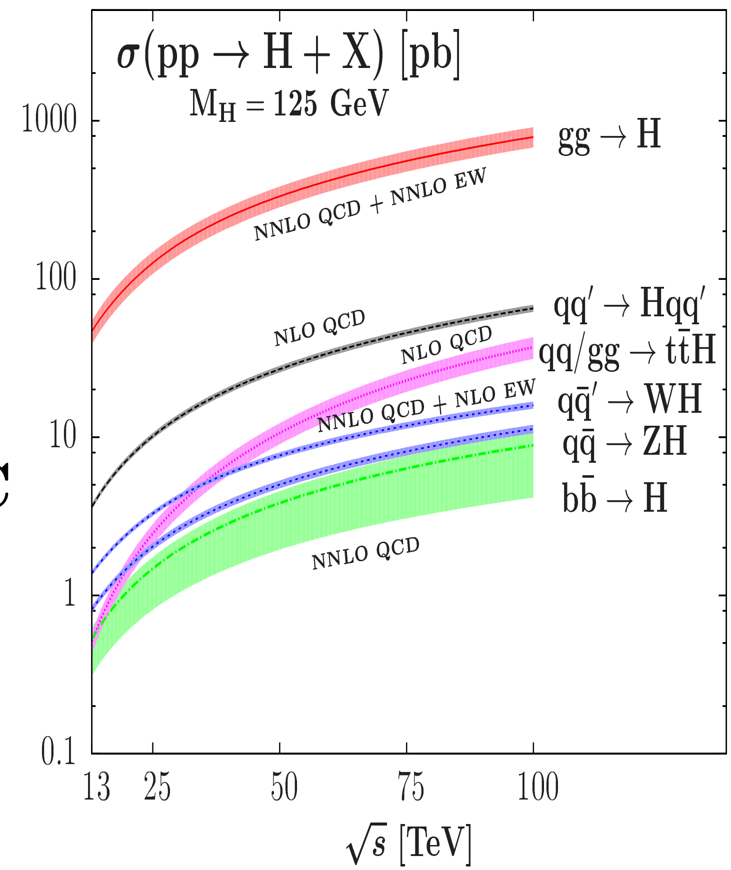
- **Uncertainty from EFT approach at N^{3}LO**

$m_{\rm loop} \gg M_H$ good for top if $M_H \lesssim 2m_t$
not above, and no b ($\approx 10\%$), W/Z loops
Estimate from exact NLO: $\Delta_{\rm eft} \approx 2-3\%$

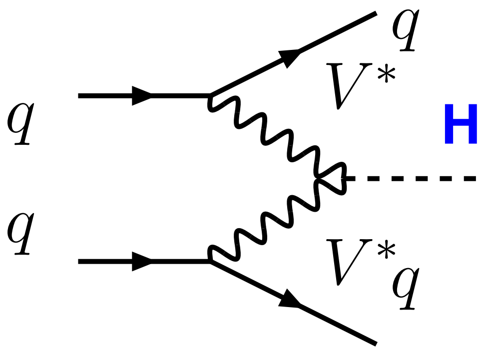
- **Include ΔBR(H$\to$X) of at most few %**

total $\Delta\sigma^{\rm NNLO}_{gg\to H\to X} \approx$ 10–20%@lHC

LHC-HxsWG; Baglio+AD $\Rightarrow$



5. SM Higgs production: WW fusion



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

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

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

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

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

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

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

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

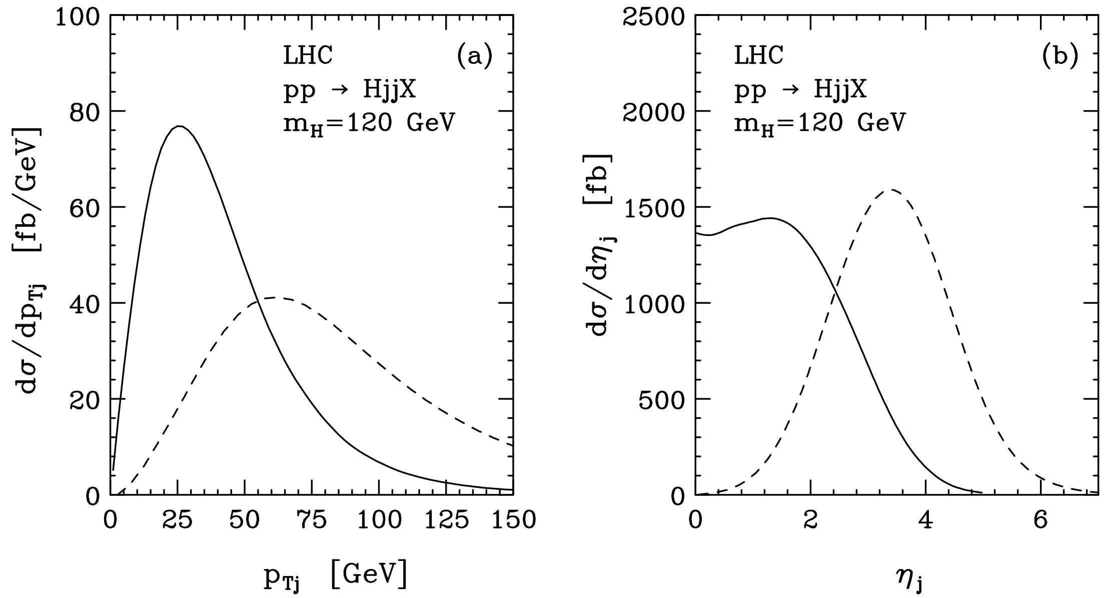
In fact: at LO in/out quarks are in color singlets and at NLO: no gluons are exchanged between first/second incoming (outgoing) quarks: QCD corrections only consist of known corrections to the PDFs!

5. SM Higgs production: WW fusion

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

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

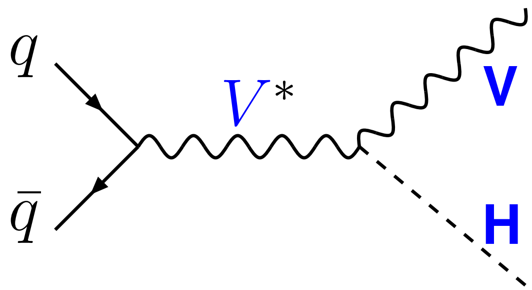
Allow to suppress the background to the level of H signal: $\mathrm{S/B} \sim 1$.



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

5. SM Higgs production: associated HV

The associated HV production:



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

Similar to $\mathrm{e^+e^-} \to \mathrm{HZ}$ process used for Higgs searches at LEP2.
Cross section $\propto \hat{\mathrm{s}}^{-1}$ sizable only for low $\mathrm{M_H} \lesssim 200$ GeV values.
Cross section for $\mathrm{W^\pm H}$ approximately 2 times larger than ZH.
Interesting final states are: $\mathrm{WH} \to \gamma\gamma\ell, \mathrm{b\bar{b}}\ell, 3\ell$ and $\mathrm{ZH} \to \mathrm{q\bar{q}}\nu\nu$.
$\mathrm{ZH} \to \ell\ell\mathrm{b\bar{b}}$ at high $\mathrm{P_T}$: jet substructure ($\mathrm{H} \to \mathrm{b\bar{b}} \neq \mathrm{g^*} \to \mathrm{q\bar{q}}$).
In fact, simply Drell–Yan production of virtual boson with $\mathrm{q^2} \neq \mathrm{M_V^2}$

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

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

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

5. SM Higgs production: associated HV

Radiative corrections needed:

– for precise determination of σ

– stability against scale variation

HO also needed to fix scales:

– renormalization $\mu_{\rm R}$ for $\alpha_{\rm s}$

– factorization $\mu_{\rm F}$ for matching.

RC parameterized by K–factor:

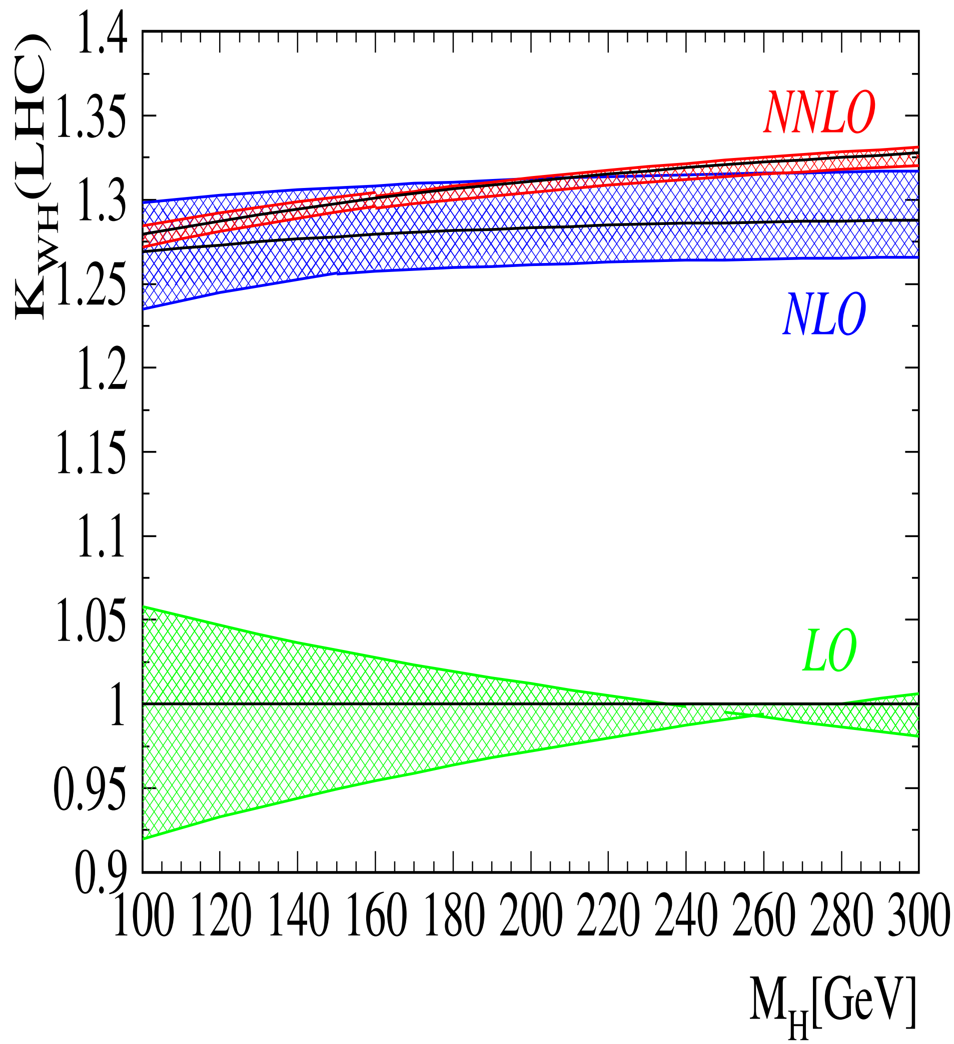
$$\mathbf{K} = \frac{\sigma_{\rm HO}(\mathbf{pp\to H+X})}{\sigma_{\rm LO}(\mathbf{pp\to H+X})}$$

Can also define K-factor at LO.

QCD RC in HV known up to NNLO

(borrowed from Drell-Yan: K$\approx$ 1.4)

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



Radiative corrections to various kinematical distributions also known

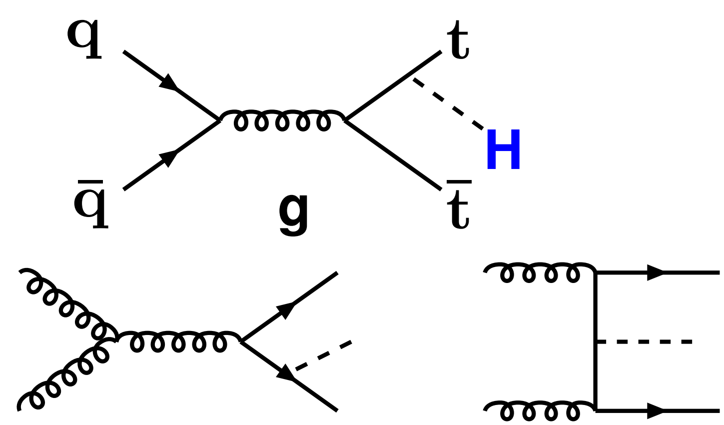
(kinematics of the process rather simple, esp. for MC implementation.)

5. SM Higgs production: 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.

Important role of kinematical distributions (e.g: $\mathrm{p_T^{top}, P_T^H}$), etc...



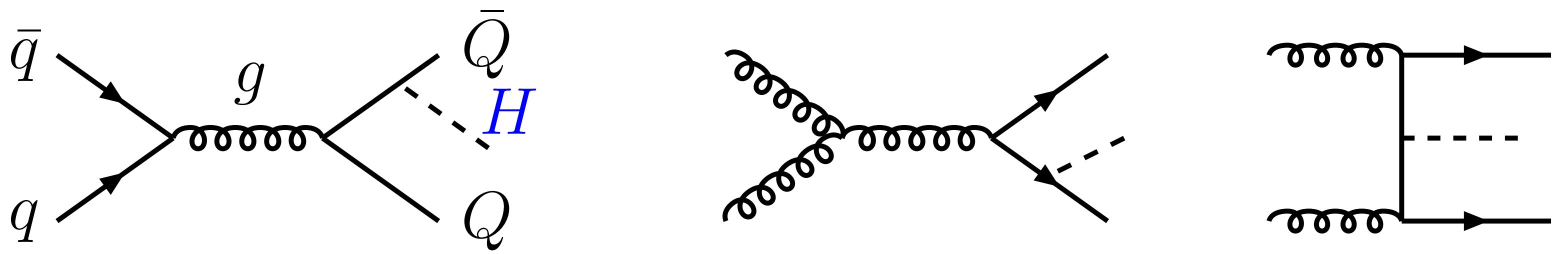
Another important process involving top quarks in the final state is single top+Higgs production: $\mathrm{pp \to tH+X}$; but with smaller rates.

- Important for a direct determination of the Htt Yukawa coupling!
- Interesting final states: $\mathrm{pp} \to \mathrm{Htt} \to \gamma\gamma + \mathrm{X}, \nu\nu\ell^{\pm}\ell^{\mp}, \mathrm{b\bar{b}}\ell^{\pm}$.
- Possibility for a 5 signal at $\sqrt{s} = 13$ TeV with a high enough luminosity.

Similar process for $\mathrm{pp} \to \mathrm{b\bar{b}H}$; small rates; approximated by $\mathrm{b\bar{b}} \to \mathrm{H}$
(works in SM extensions in which bbH coupling is enhanced, e.g. MSSM).

5. SM Higgs production: Htt production

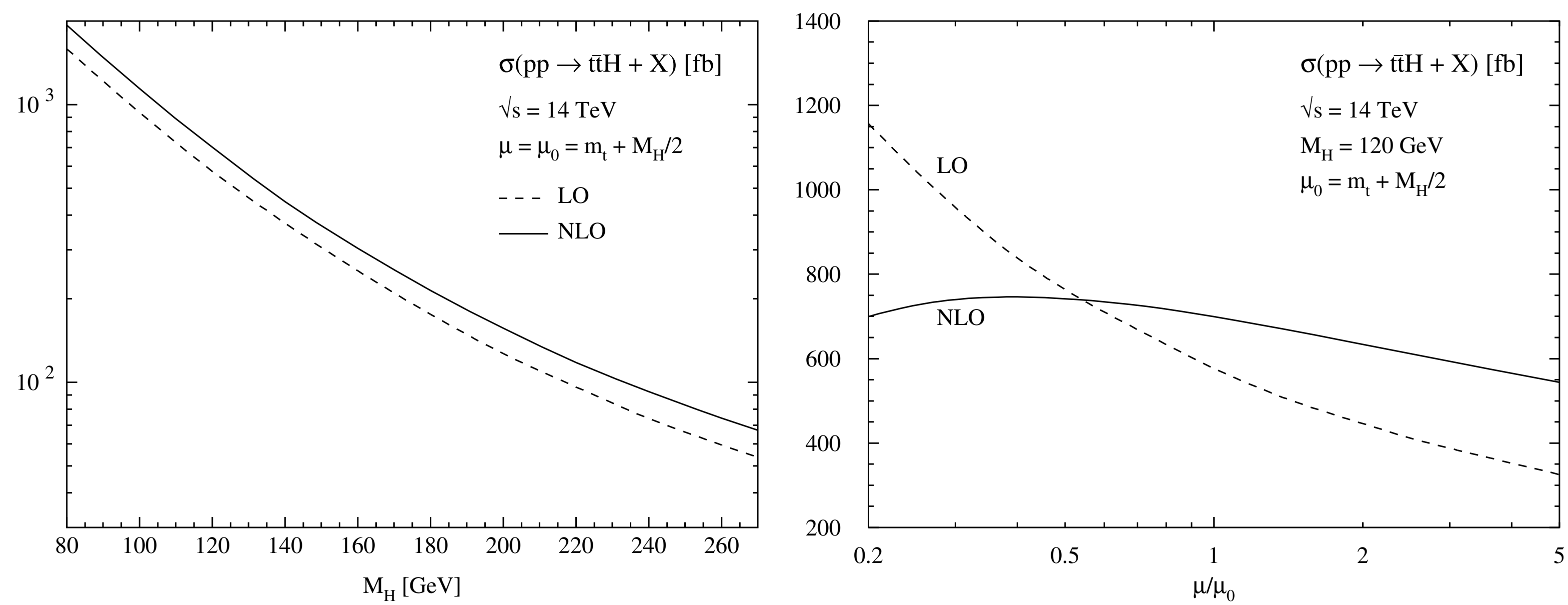
Most complicated process for Higgs production in pp as many channels:



NLO QCD corrections also calculated: Spira et al., Dawson et al.

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

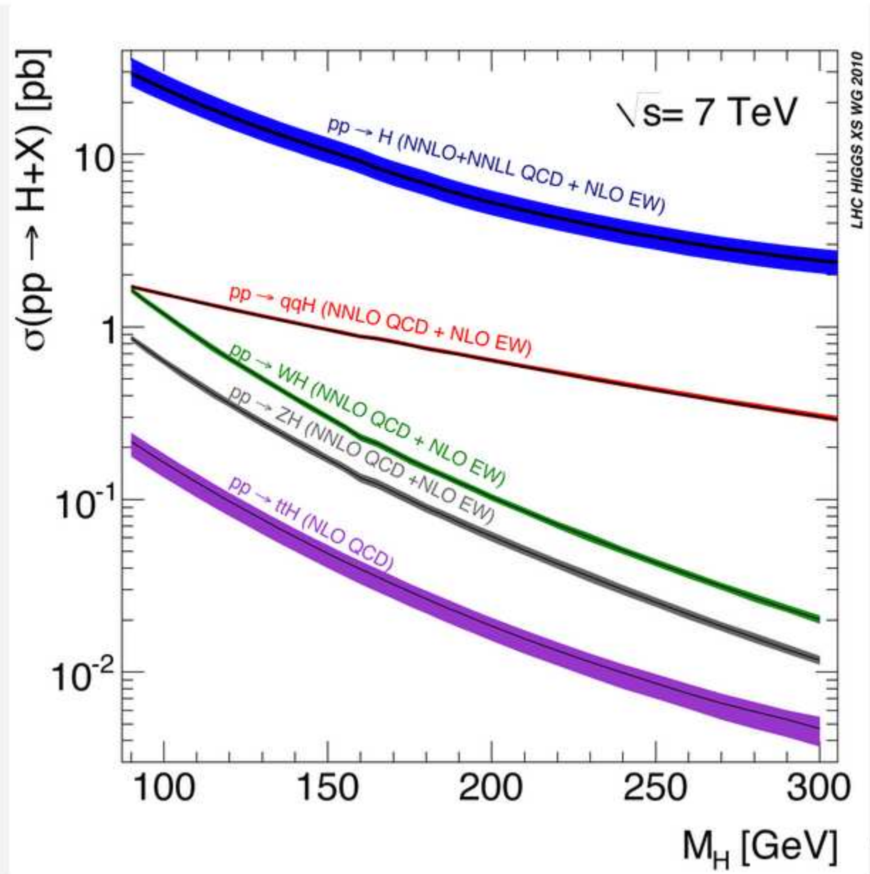
Small corrections to kinematical distributions (e.g: $\mathrm{p_T^{top}}$, $\mathrm{P_T^H}$), etc.

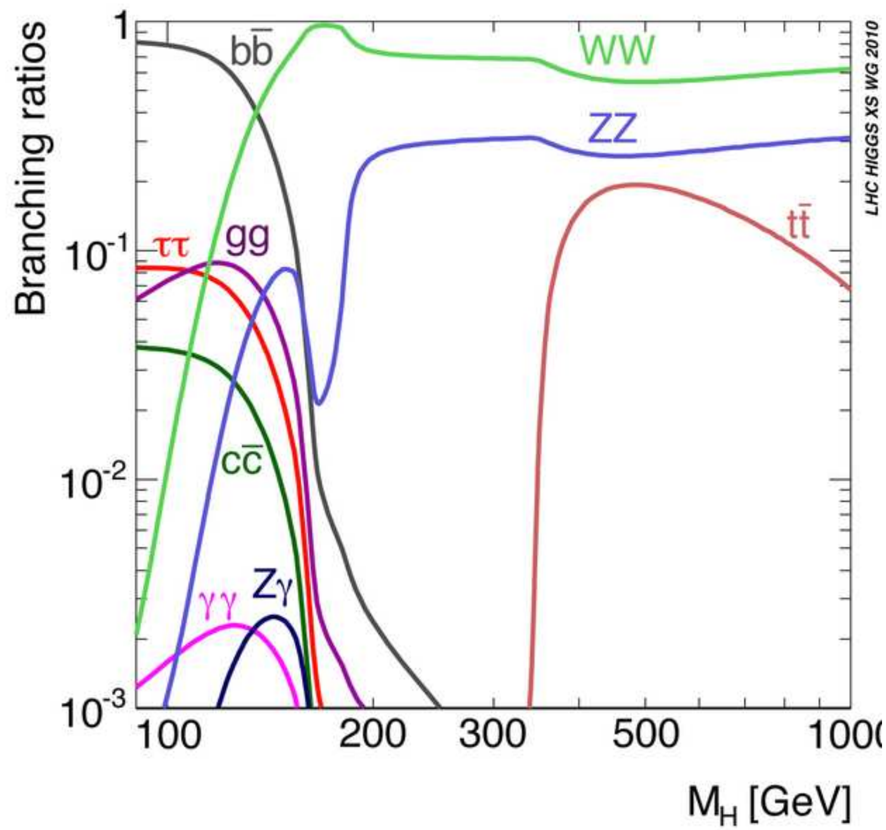


QCD corrections larger for $\mathrm{pp} \to \mathrm{b\bar{b}H}$ (K$\approx 1.5)$ and large scale uncert.

5. SM Higgs production: wrap up

Knowledge of the various cross sections times BR just before discovery summarized by LHC Higgs xsection working group, rep. CERN-2011-002.





The Higgs discovery was a great challenge, but with all this information (a result of 30 years of hard work), the expectations were rather optimistic:

5. SM Higgs production: wrap up

Latest expectations of ATLAS/CMS:

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

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

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

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

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

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

Slightly better at 8 TeV and higher $\mathcal{L}$.

Subleading channels might help a bit:

– VBF/VH and $gg\to H\to\tau\tau$

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

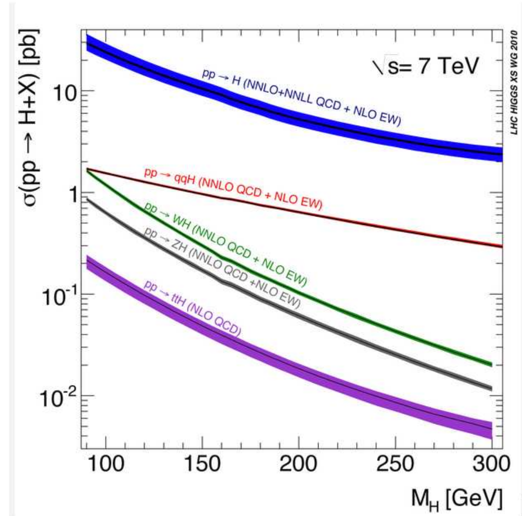
Full LHC: same as lHC plus some others

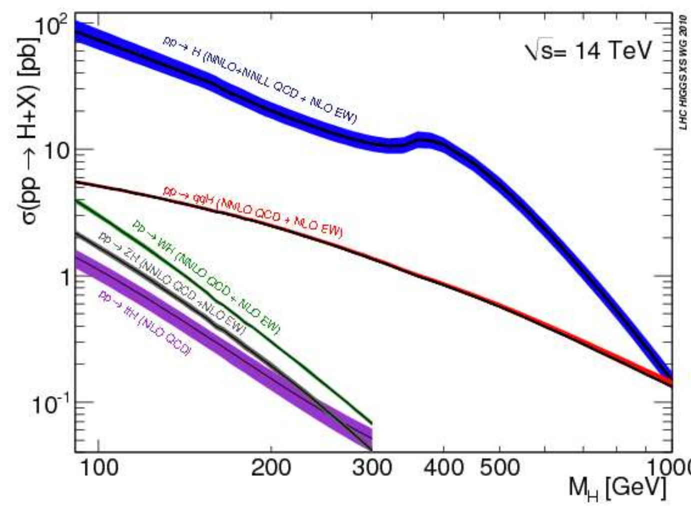
– VBF: $qqH\to\tau\tau,\gamma\gamma,ZZ^*,WW^*$

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

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

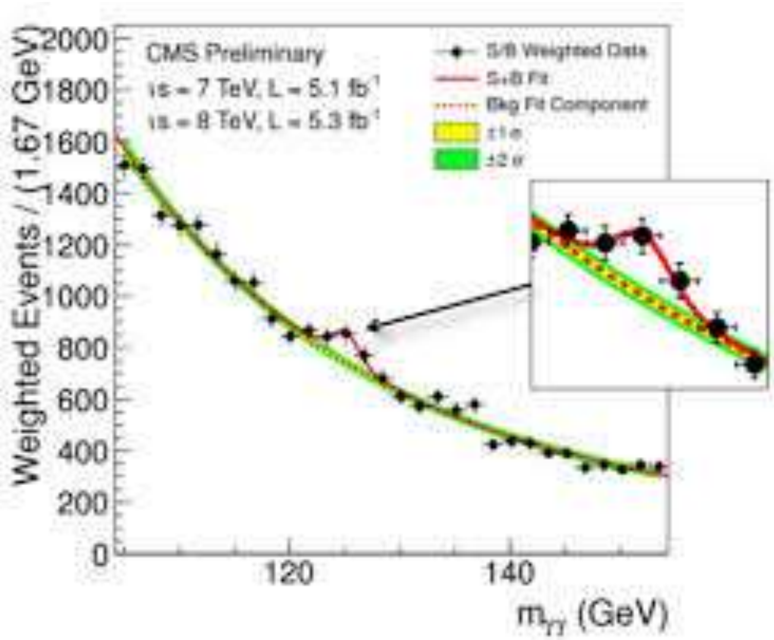
Conclusion? Mission accomplie!

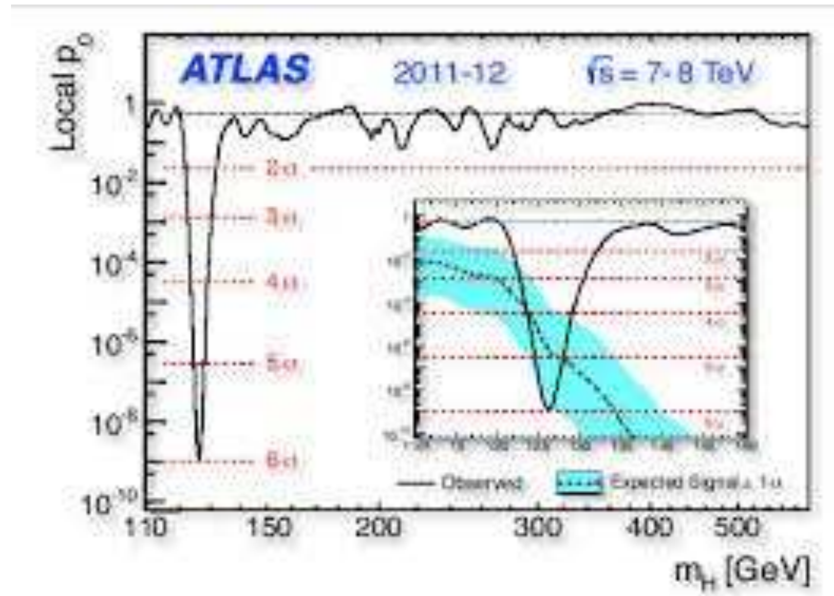




5. SM Higgs production: wrap up

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





6. Higgs tests at the LHC

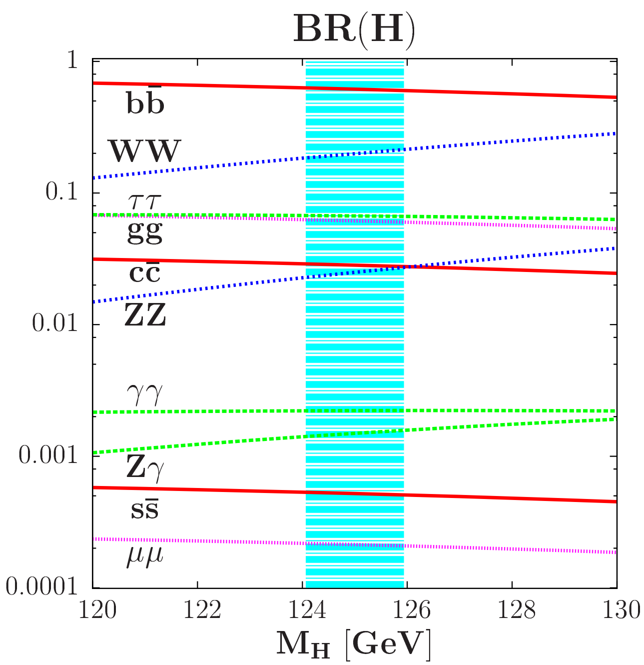
So what should we do now and in the next 10–30 years in Particle Physics?

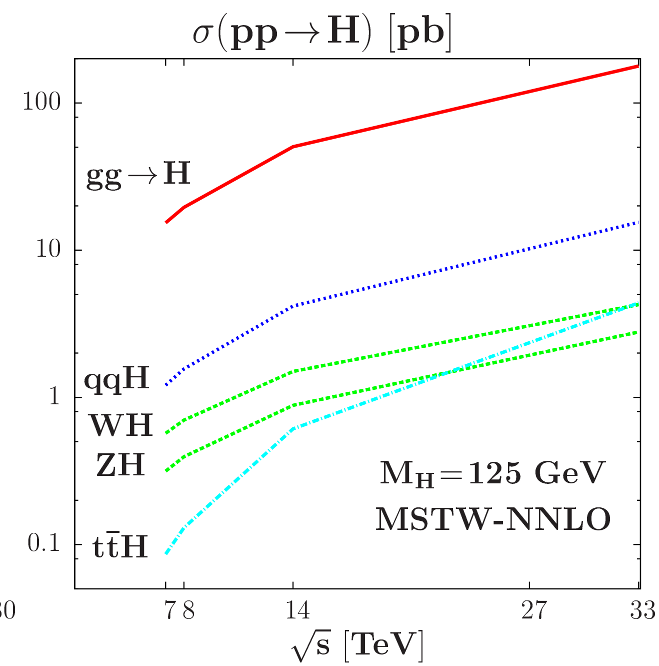
Need to check that H is indeed responsible of sEWSB (and SM-like?)

$\Rightarrow$ **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.**

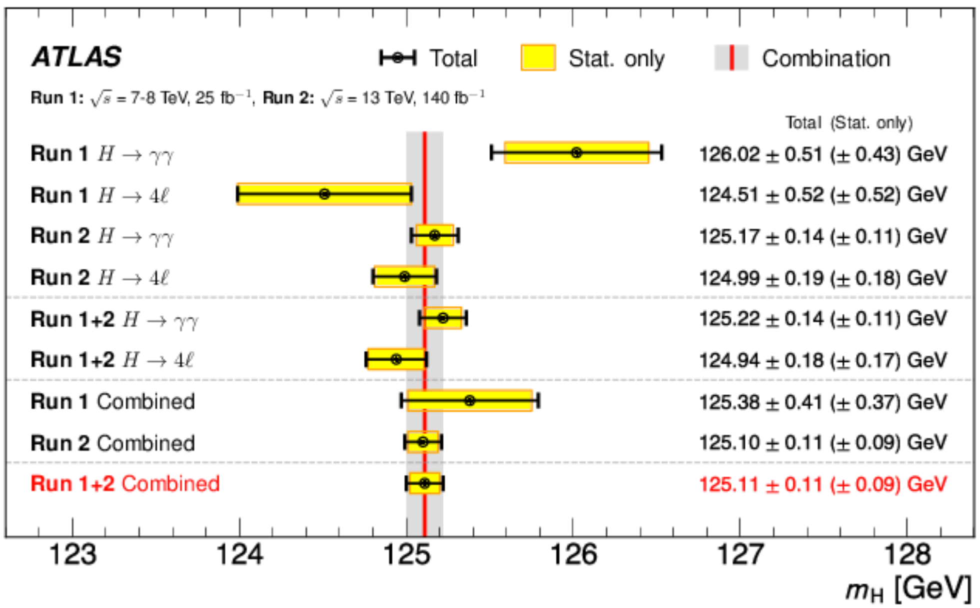
Possible for $M_H \approx$ 125 GeV as all production/decay channels useful!

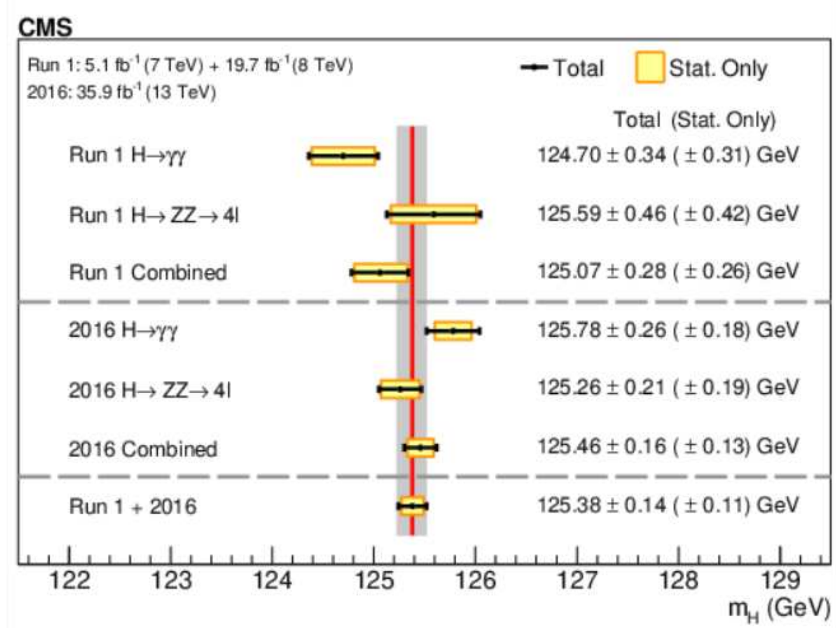




6. Higgs tests at the LHC

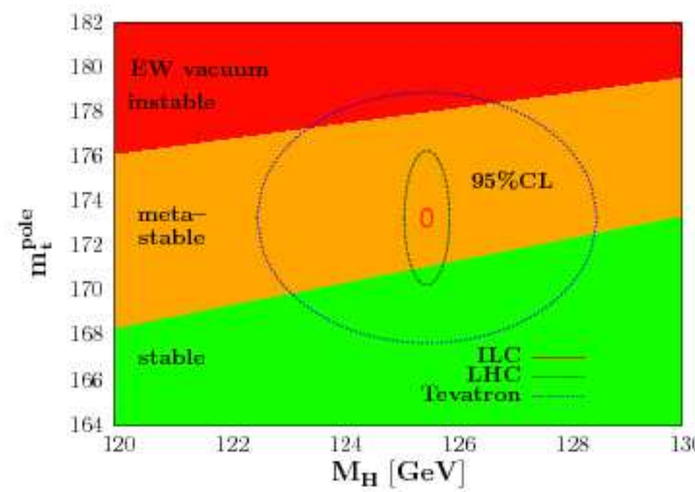
A) a very precise measurement of Higgs boson mass in $\mathrm{H} \to \mathrm{ZZ}, \gamma\gamma$:





The value of $\mathrm{M_H}$ at 0.1% level is important for the issue of the EW vacuum stability; but the uncertainty is mostly coming from the errors on the values of $\mathrm{m_t}$ and α_s....

These parameters need to be measured with a much better accuracy! ILC or FCC-ee?



6. Higgs tests at the LHC

A) a precise measurement of total Higgs decay width via interferenc e:

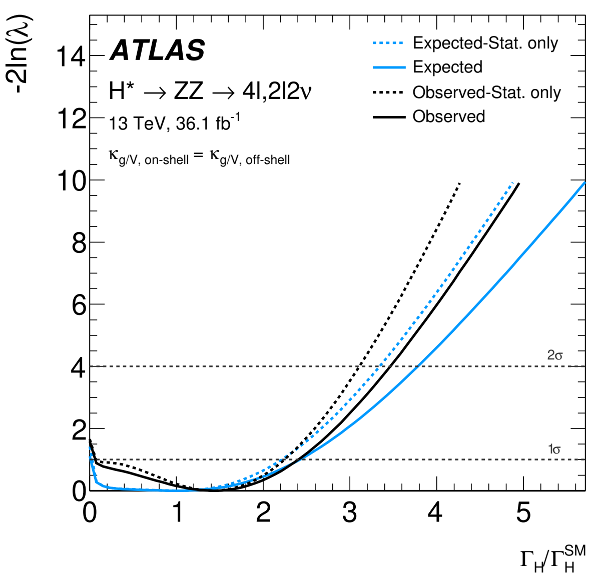
$\Gamma_H^{SM} = 4.07$ MeV $\Rightarrow$ too small to be resolved experimentally.

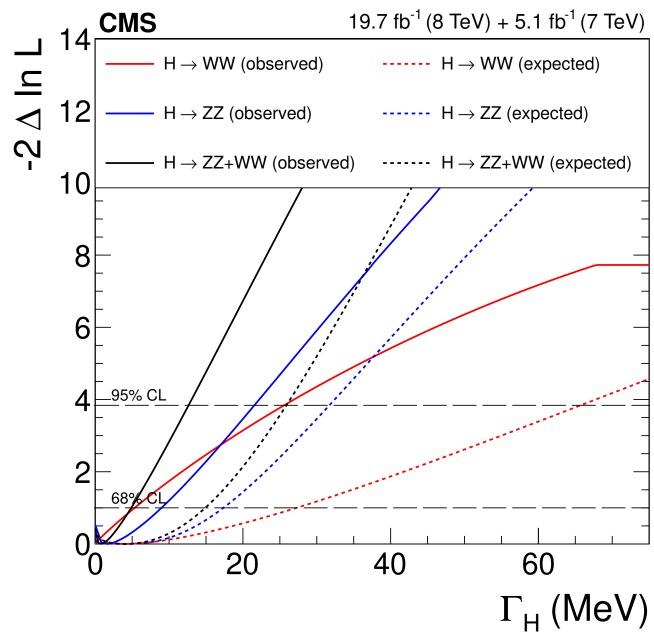
If $M_H \gtrsim 200$ GeV, $\Gamma_H > 1$GeV $\Rightarrow$ possible in $H \to ZZ \to 4\ell$.

But in $pp \to H \to ZZ \to 4\ell$, about 20% are for $M_{4\ell} \gtrsim 2M_Z$.

In fact: $\sigma^{\rm on-shell}_{gg\to H\to 4\ell} \propto g^2_{ggH}$, $\sigma^{\rm off-shell}_{gg\to H\to 4\ell} \propto g^2_{ggH}\Gamma_H \Rightarrow$ interf $\propto g_{ggH}\sqrt{\Gamma_H}$

Indirect measurement of Γ_H via interference with $pp \to ZZ$ continuum:





The constraints are starting to be serious: $\Delta\Gamma_H/\Gamma_H^{SM} \lesssim \mathcal{O}(1)$!

6. Higgs tests at the LHC

B) Check of the CP quantum numbers: is it a pure 0^{++} scalar particle?

For the spin, there is no suspense: the observed state decays into $\gamma\gamma$

- **it cannot be spin-1: Landau–Yang theorem forbids $V \to \gamma\gamma$ channel;**
- **it could be spin–2 like graviton? but miracle that couplings fit that of H, "prima facie" evidence against it as e.g.: $c_g \neq c_\gamma$ and $c_V \gg 35 c_\gamma$ ....**

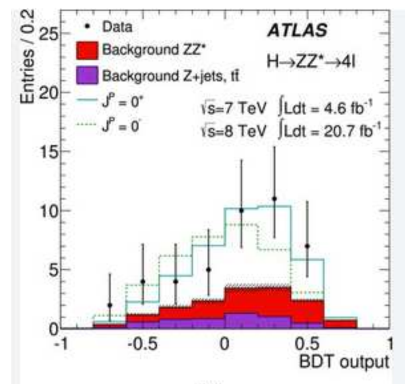
CP quantum numbers: is it a pure CP-even, CP-odd, or a CP–mixture?

More important: is there CPV in Higgs?
ATLAS and CMS CP made analyses for pure CP–even versus pure CP–odd

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

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

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



But problem with picture: pure CP-odd does not couple to VV@tree-level; in $H \to ZZ^* \to 4\ell$, only the CP-even part of H coupling is projected out! True probe via production/decay involving fermions as coupling democratic ex: spin-correlations in $q\bar{q} \to HZ \to bb\ell\ell$ or $gg/q\bar{q} \to Ht\bar{t} \to b\bar{b}t\bar{t}$.

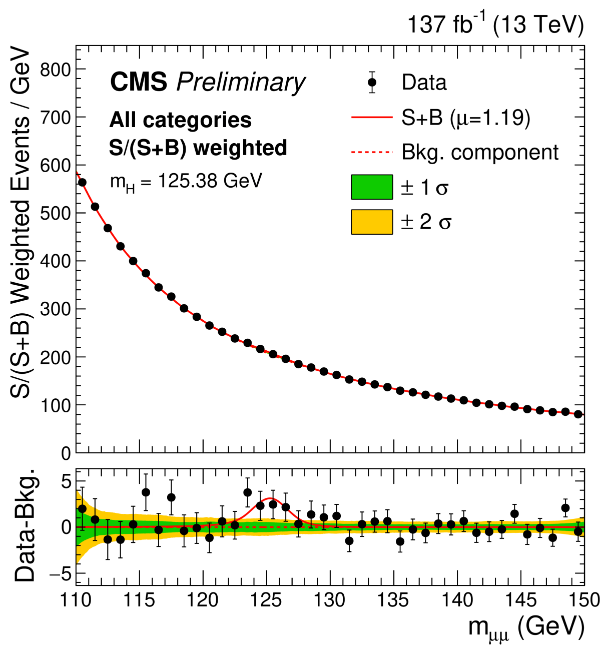
Tests are more challenging and need much more statistics $\Rightarrow$ HL–LHC.

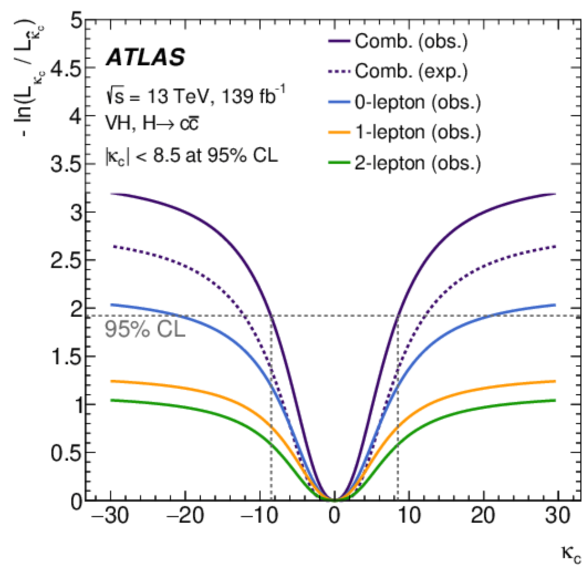
6. Higgs tests at the LHC

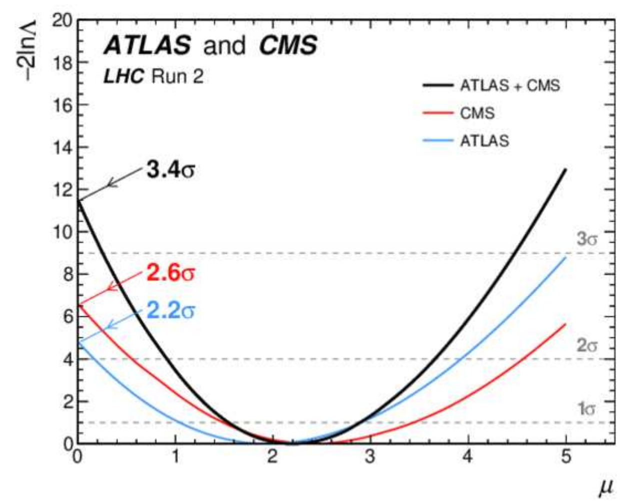
C) Probe very rare H decays that allow additional/unknown information:

- $\mathrm{H} \to \mu^+\mu^-$ **to probe second generation fermion couplings;**
- $\mathrm{H} \to c\bar{c}$ **to probe second generation quark couplings (difficult);**
- $\mathrm{H} \to Z\gamma$ **which has information that is complementary to** $\mathrm{H} \to \gamma\gamma$**.**

$\mathbf{H} \to \mu^+\mu^-$ $\qquad$ $\mathbf{H} \to c\bar{c}$ $\qquad$ $\mathbf{H} \to Z\gamma$







Observed at 3.0σ $\qquad$ $\kappa_c \leq 8.5$ @95%CL $\qquad$ **Observed at 3.4**σ

Need much larger statistic for much better measurements $\Rightarrow$ **HL-LHC**

6. Higgs tests at the LHC

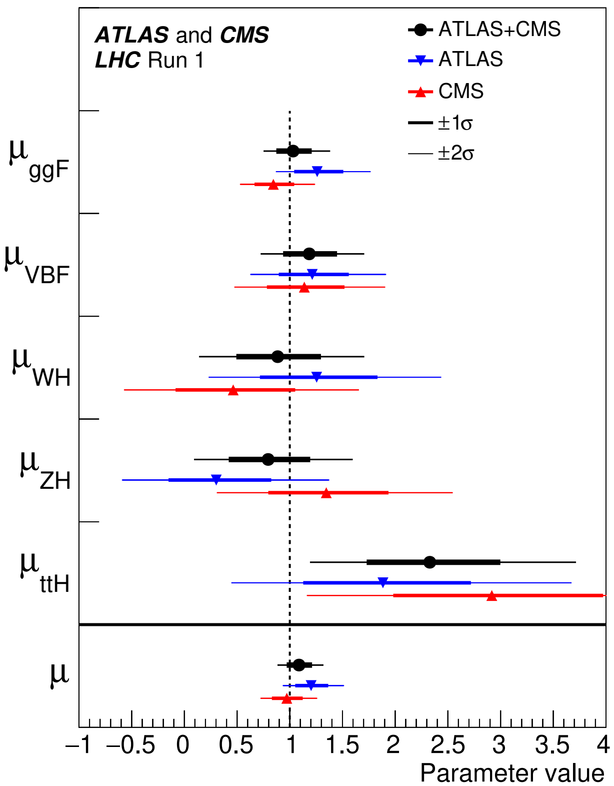
D) Precise measurements of the Higgs decay/production rates:

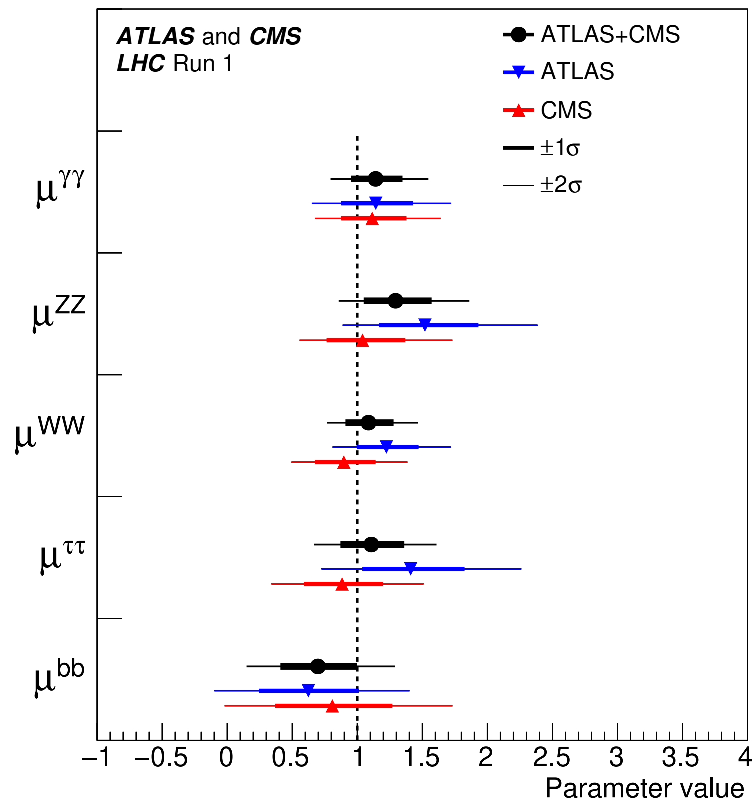
- most Higgs decays have been probed: $\mathrm{H \to ZZ, WW}, \gamma\gamma, \mathrm{bb}, \tau\tau, \mu\mu$;

- all Higgs production channels contributed to Higgs: ggF, VBF, VH, ttH;

For one production channel, construct H signal strengths in given decay:

$$\mu_{\mathbf{XX}} = \frac{\sigma(\mathbf{pp \to H \to XX})}{\sigma(\mathbf{pp \to H \to XX})|_{\mathbf{SM}}} = \frac{\sigma(\mathbf{pp \to H}) \times \mathrm{BR}(\mathbf{H \to XX})}{\sigma(\mathbf{pp \to H})|_{\mathbf{SM}} \times \mathrm{BR}(\mathbf{H \to XX})|_{\mathbf{SM}}}$$



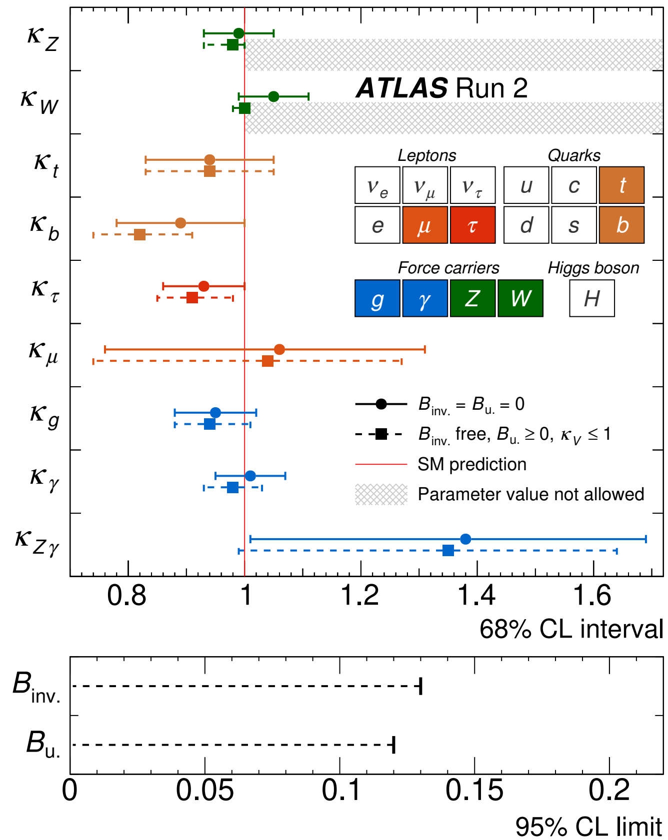


6. Higgs tests at the LHC

D) Precise measurements of the Higgs couplings to particles:

$$\kappa_{\rm x}^2 = \sigma({\rm x})/\sigma({\rm x})|_{\rm SM} = \Gamma({\rm xx})/\Gamma({\rm xx})|_{\rm SM} = {\rm g}^2_{\rm Hxx}/{\rm g}^2_{\rm Hxx}|_{\rm SM}$$

$$\Gamma({\rm VV}) \to \kappa_{\rm V}^2,$$
$$\Gamma({\rm ff}) \to \kappa_{\rm f}^2,$$
$$\sigma({\rm VH}) \to \kappa_{\rm V}^2,$$
$$\sigma({\rm ttH}) \to \kappa_{\rm t}^2,$$
$$\sigma({\rm vbf}) \to 0.74\kappa_{\rm W}^2 + 0.26\kappa_{\rm Z}^2$$
$$\Gamma(\gamma\gamma) \to \kappa_\gamma^2 = 1.5\kappa_{\rm W}^2 + 0.1\kappa_{\rm t}^2 - 0.7\kappa_{\rm t}\kappa_{\rm W},$$
$$\sigma({\rm ggH}) \to \kappa_{\rm g}^2 = 1.06\kappa_{\rm t}^2 - 0.07\kappa_{\rm t}\kappa_{\rm b}$$



$$\kappa_{\rm H}^2 = 0.57\kappa_{\rm b}^2 + 0.22\kappa_{\rm W}^2 + 0.06\kappa_\tau^2 + 0.03\kappa_{\rm Z}^2 + 0.03\kappa_{\rm c}^2 + 0.0023(\kappa_\gamma^2 + \kappa_{{\rm Z}\gamma}^2)$$

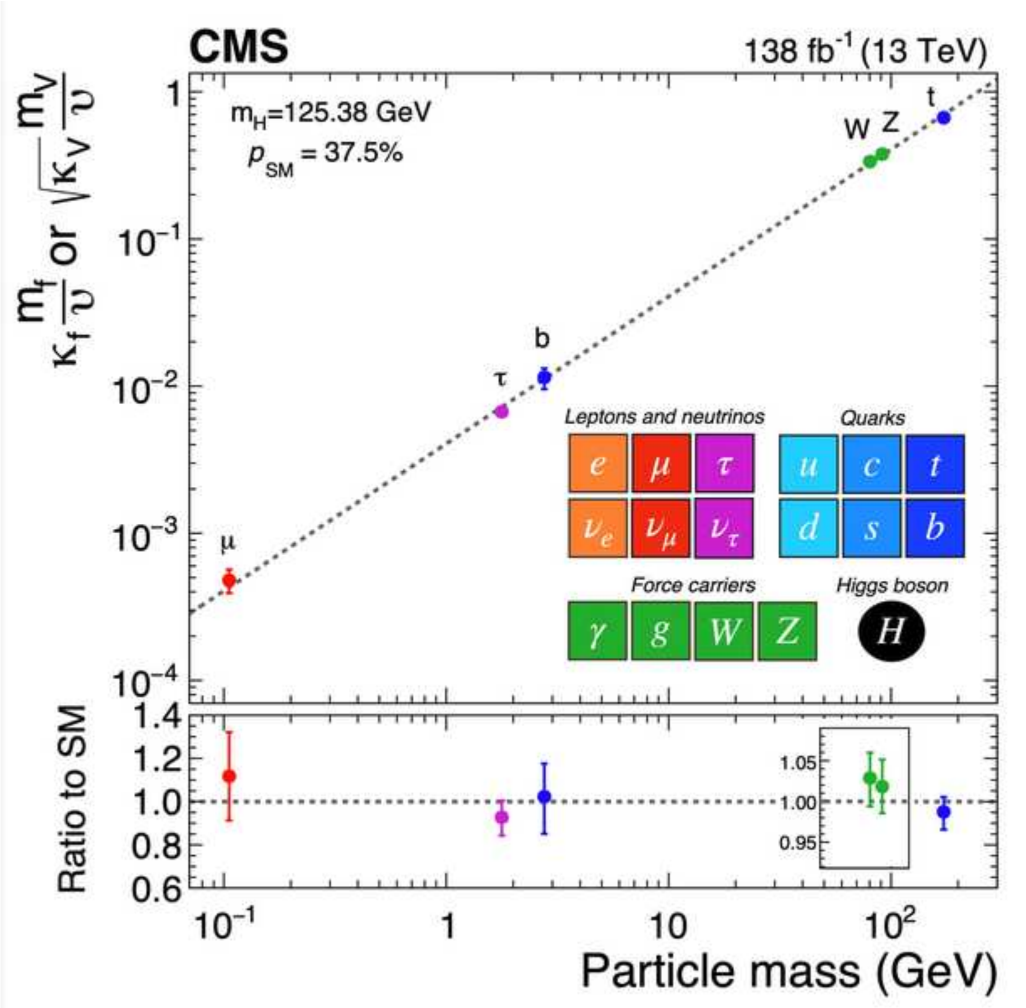
Global ATLAS fit gives BR(H$\to$ invisible) $\lesssim 0.13$@68%CL

6. Higgs tests at the LHC

D) Precise measurements of the Higgs couplings to particles:

- many Higgs couplings (gauge bosons, 3 generation fermions) measured;
- even the coupling to second generation muons probed; also recent $HZ\gamma$.

H couplings to particles are proportional to their mass as predicted in SM!

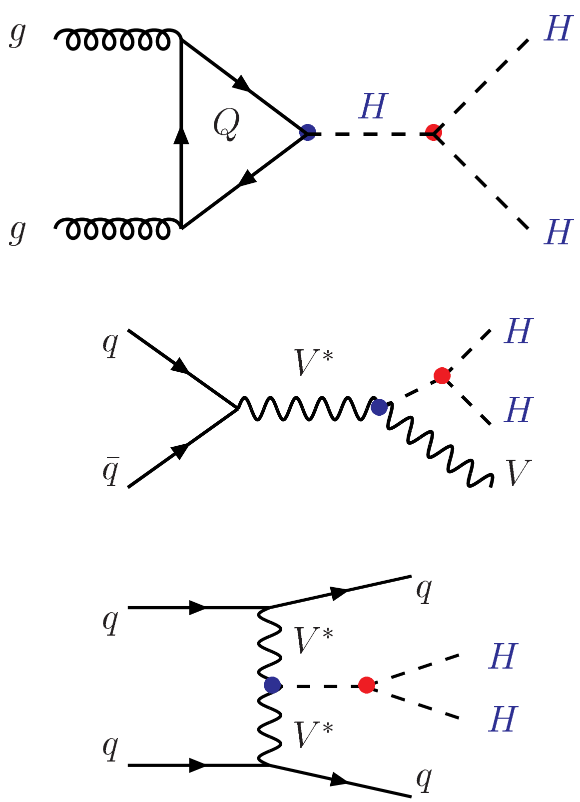


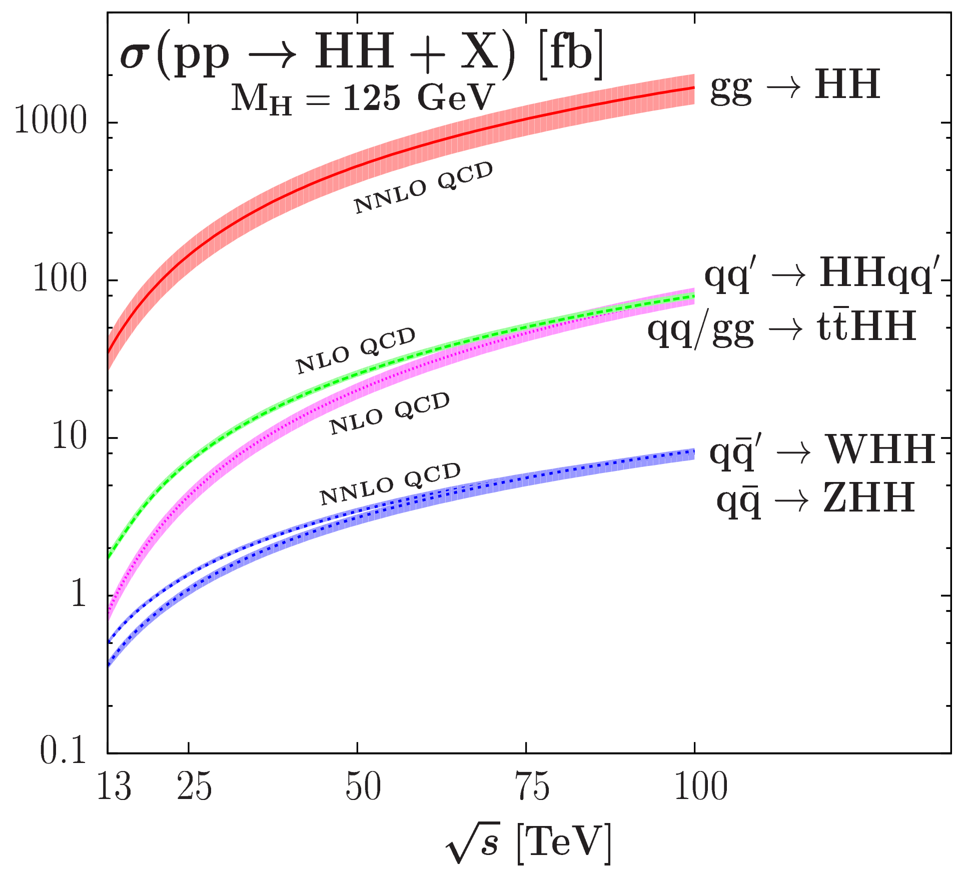
6. Higgs tests at the LHC

E) Measure the Higgs self-couplings $\lambda_{H^3}, \lambda_{H^4} \Rightarrow$ access to V_H.

- λ_{H^3} **is accessible in double Higgs production:** $pp \to HH + X$;
- g_{H^4} **is hopeless to measure, needs pp→HHH+X with too low rates.**

Processes relevant processes for double Higgs production at the LHC:





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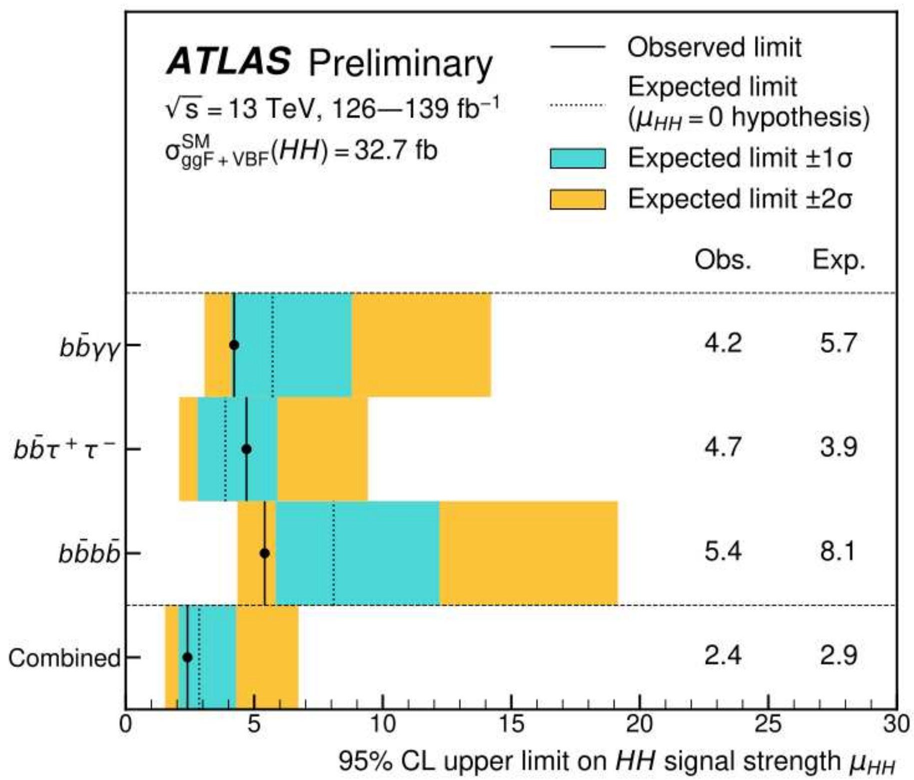
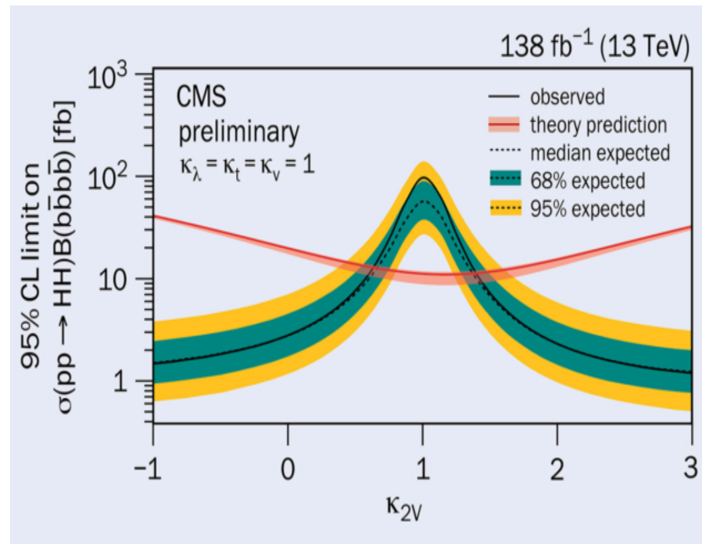
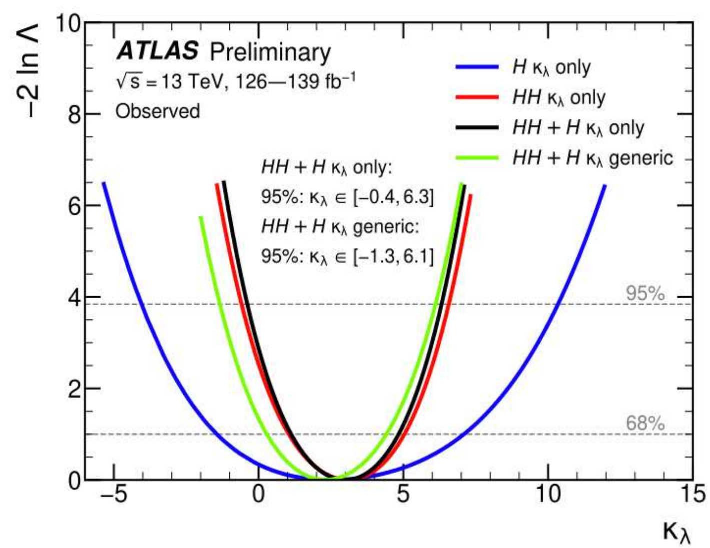


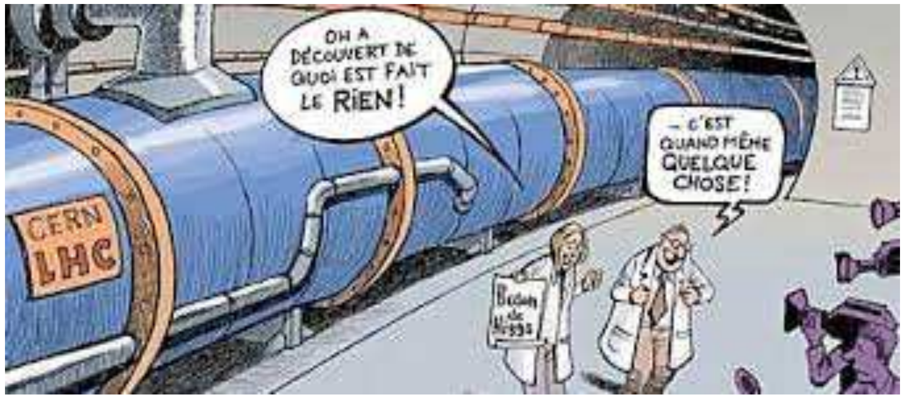




7. Beyond the Standard Model?

Now that the Higgs is discovered and the SM is confirmed in a spectacular way, is Particle Physics closed? Should we stop and just go to the beach?

Of course not!



Despite of its successes, the SM is not considered to be satisfactory and is only an effective manifestation of a more fundamental theory...

... that cures certain serious problems that the SM left aside....

- **Problems of aesthetic nature: too complex and too many ingredients, we want a theory with a few parameters and basic ingredients/principles.**
- **Problems of experimental nature and non-conformity to the microcosm: the SM does not explain all the phenomena that are observed in Nature.**
- **Problems of theoretical consistency: the SM is not extrapolable up to the ultimate energies $\Rightarrow$ we need a new paradigm to achieve this aim.**

7. Beyond the Standard Model?

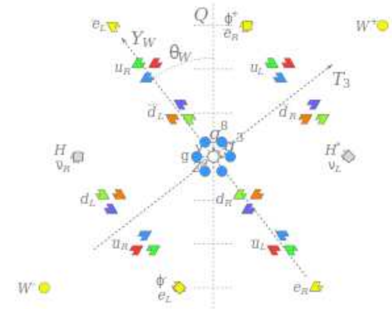
• **Problems of aesthetic nature: SM too complex and too many ingredients, we want a theory with a few parameters and basic ingredients/principles.**

• **Too many ingredients put by hand:**

– needs 19 parameters to describe everything;

– fermion masses very different from another;

– symmetry breaking is had-hoc/non-natural.



• **Does not include gravitation:**

– desirable at very high energies;

– but no quantum theory so far,

– graviton of spin 2 complicated.

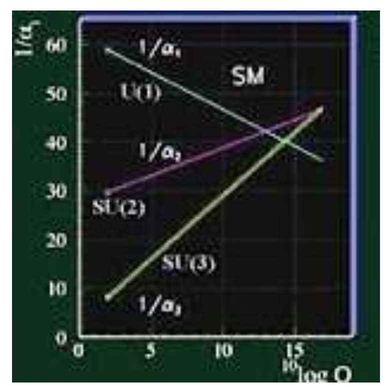
• **Unification of interactions?**

– 3 gauge groups with 3 different couplings,

– better: only one group and one coupling,

– coupling unification at a high scale?

– the three couplings do not converge.

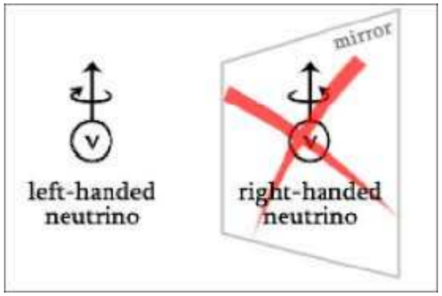


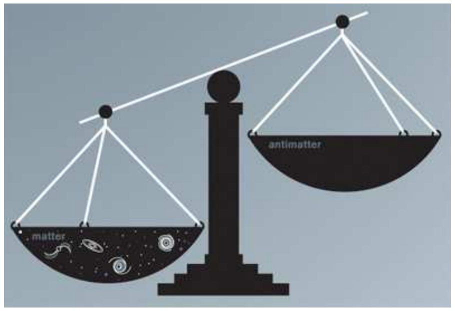
7. Beyond the Standard Model?

• **Problems of experimental nature and non-conformity to the microcosm: the SM does not explain all the phenomena that are observed in Nature.**

• **The neutrinos are massless:**

– in the SM, neutrinos are left-handed,
– experiment: neutrinos oscillate $\Rightarrow$ massive;
– their mass is not coming from the Higgs,
– we need right-handed neutrinos ($\neq$ left).



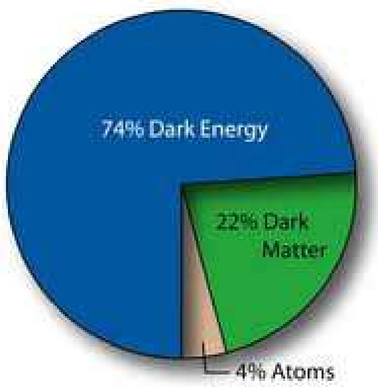


• **No baryon asymmetry in the universe:**

– there is a one billion p for a single $\bar{\mathrm{p}}$,
– but at early times, CP conserved and $\mathrm{n_p = n_{\bar{p}}}$,
– why there is such an asymmetry now?

• **There is no Dark Matter particle:**

– known matter makes $\approx$4% of energy of Universe;
– $\approx$ 25% of it is a dark or invisible matter;
– Astroparticle: must be massive and cold ($\mathrm{v \ll c}$);
– in the SM, there is not a particle which is: neutral, weakly interacting, massive and stable.



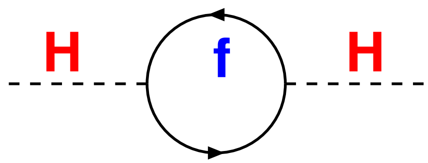
7. Beyond the Standard Model?

• Problems of theoretical consistency: the SM is not extrapolable up to the ultimate energies ⇒ we need a new paradigm to achieve this aim.

• The Higgs should have mass of order of the W,Z masses i.e. $\mathcal{O}$(100 GeV):
– required by mathematical consistency, conservation of probabilities, etc...
– more natural to solve a problem at 100 GeV with "object" of 100 GeV mass.

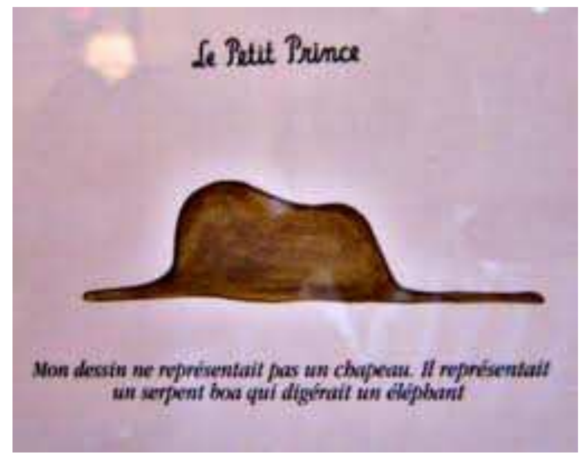
• But we should include all quantum corrections to the Higgs mass:
⇒ contributions to M_H of order M_P while they should be $\approx M_{W,Z}$...

$$\Delta M_H^2 \;\equiv$$



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

– enormous hierarchy $M_P \gg M_{W,Z}$;
– this hierarchy seems very unnatural.



• No symmetry to protect M_H from high scales?
– gauge symmetry: protects the photon mass (vanishing corrections);
– L/R or chiral symmetry: protects fermion masses (small corrections).

Hierarchy problem: M_H prefers to be close to the high scale...

7. Beyond the Standard Model?

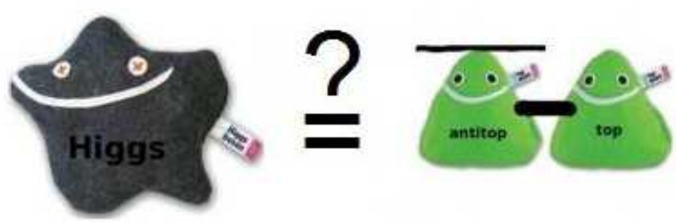
Three main avenues to solve the hierarchy problem of the SM.

I) The Higgs is not an elementary spin-0 particle, but it is composite.

The Higgs boson is the sole fundamental particle of spin equal to zero:
if the Higgs is not fundamental $\Rightarrow$ the hierarchy problem disappears.

- **The Higgs is a bound state of two fermions:**

one can have a bound state or condensate:
$s = \frac{1}{2} \oplus \frac{1}{2} = 0 \Rightarrow$ **scalar (like the π meson).**
but the particle should be rather massive.
Only option in SM: top-antitop condensate.



- **Even more radical is Technicolor:**

all SM particles are composite states
(here is another layer in the onion);
$\equiv$ **QCD but at higher scale $\Lambda = 1$ TeV,**
$\Rightarrow$ **H bound state of two techni-fermions.**

- **In both cases $\Rightarrow$ Higgs properties $\neq$ of those of the standard H.**

Both theories are of strong interaction $\Rightarrow$ constrained by experiment.

7. Beyond the Standard Model?

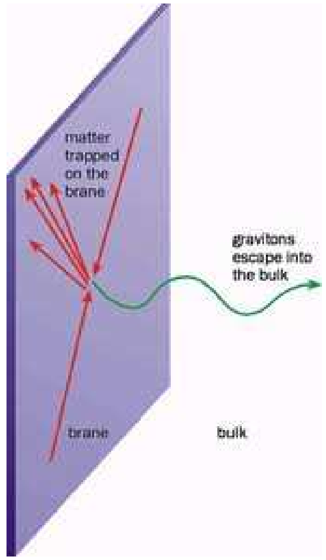
Three main avenues to solve the hierarchy problem of the SM.

II) Additional space-time dimensions at the scale of a few TeV?

We could have a 5th space-time dimension where at least the s=2 gravitons propagate.

Gravity: effective scale is $M_P^{\rm eff} \approx \Lambda \approx$ TeV, not $M_p = 10^{18}$GeV; gravity now in the game.

Several possibilities to realize the scenario: large, warped, universal extra dimensions, ...



Enormous impact on particle physics!

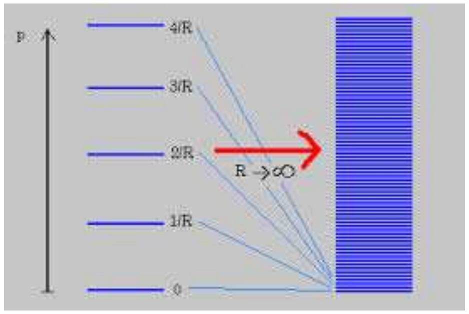
(with solutions to other SM problems).

- **But we still need symmetry breaking:**

– the same Higgs mechanism as in the SM,
– but also possibility of a Higgs-less world.

- **Known particles are the zero modes of**

– an infinite tower of Kaluza–Klein excitations,
– new heavy partners of the fermions/bosons.



Plenty of new exotic particles to discover and study at LHC and beyond!

7. Beyond the Standard Model?

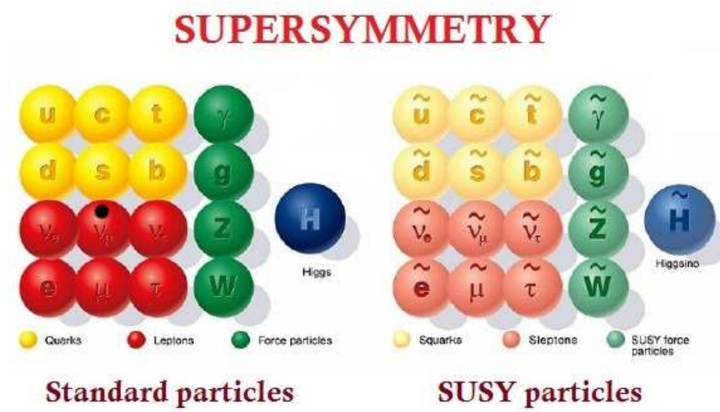
Three main avenues to solve the hierarchy problem of the SM.

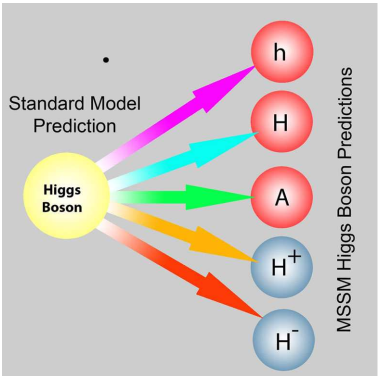
III) Supersymmetric theories (SUSY) or how to double the world.

Supersymmetry is considered to be the most attractive extension of the SM:

- relates the s=$\frac{1}{2}$ fermions to s=0,1 bosons;
- relates internal and space-time symmetries;
- if SUSY is made local, we recover gravity;
- is naturally present in Superstrings theory.
  - To each particle $\Rightarrow$ a superparticle (sfermions of s=0 and gauginos of s=$\frac{1}{2}$).
  - Enlarged Higgs sector: h,H,A,H^+, H^- (two doublets of scalar Higgs fields).
- Cancels divergences Λ^2 and hierarchy;
- $\mu^2 < 0$ naturally via quantum effects;
- leads to unification of gauge couplings;
- has the ideal candidate for Dark Matter...

A whole new continent to explore at the LHC!





8. Simples extensions of the SM: singlets

Simplest SM extension: add one scalar ϕ that develops a vev v_ϕ; it has:

$$\mathbf{V}(\Phi,\phi) = \lambda(\Phi^\dagger\Phi)^2 + \mu^2\Phi^\dagger\Phi + \lambda_{\mathbf{HH'}}\Phi^\dagger\Phi\phi^2 + \lambda_\phi\phi^4 + \mu_\phi^2\phi^2$$

after EWSB ($\mu_\phi^2 < 0$), one has two Higgs bosons H and H' which mix

$$\begin{pmatrix}\mathbf{H}\\ \mathbf{H'}\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix} = \begin{pmatrix}\mathrm{Re}\Phi^0\\ \mathrm{Re}\phi^0\end{pmatrix} \text{ with } \tan 2\theta = \frac{\lambda_{\mathbf{HH'}}\mathbf{v}\mathbf{v}_\phi}{\lambda_\phi \mathbf{v}_\phi^2 - \lambda\mathbf{v}}$$

The masses of the two physical states read (H is the SM-like boson) :

$$\mathbf{M}^2_{\mathbf{H/H'}} = (\lambda\mathbf{v} + \lambda_\phi\mathbf{v}_\phi) \mp |\lambda\mathbf{v}^2 - \lambda_\phi\mathbf{v}_\phi^2|\sqrt{1+\tan^2 2\theta}$$

The model has 3 parameters (on top of v and $\mathbf{M_H}$): $\mathbf{M_{H'}}, \lambda_{\mathbf{HH'}}, \sin\theta$ with

$$\lambda = \frac{\mathbf{M_H^2}}{2\mathbf{v}^2} + \frac{\Delta\mathbf{M}^2_{\mathbf{H'H}}\mathbf{s}_\theta^2}{2\mathbf{v}^2}, \lambda_\phi = \frac{2\lambda^2_{\mathbf{HH'}}\mathbf{v}^2}{\mathbf{s}^2_{2\theta}\Delta\mathbf{M}^2_{\mathbf{H'H}}}\left(\frac{\mathbf{M_H^2}}{\Delta\mathbf{M}^2_{\mathbf{H'H}}} - \mathbf{s}_\theta^2\right), \mathbf{v}_\phi = -\frac{\Delta\mathbf{M}^2_{\mathbf{H'H}}\mathbf{s}_{2\theta}}{2\lambda_{\mathbf{HH'}}\mathbf{v}}$$

H' and H will share the SM Higgs couplings to fermions and gauge bosons:

$$\mathcal{L}_{\mathbf{SM}}^{\mathbf{HH'}} = (\mathbf{H}\mathbf{c}_\theta - \mathbf{H'}\mathbf{s}_\theta)\Big[\frac{2\mathbf{M_W^2}}{\mathbf{v}}\mathbf{W}^+_\mu\mathbf{W}^{\mu-} + \frac{\mathbf{M_Z^2}}{\mathbf{v}}\mathbf{Z}^\mu\mathbf{Z}_\mu - \sum_\mathbf{f}\frac{\mathbf{m_f}}{\mathbf{v}}\bar{\mathbf{f}}\mathbf{f}\Big]$$

The trilinear couplings are slightly more complicated than in the SM; ex:

$$\mathcal{L}_{\mathbf{scal}}^{\mathbf{HH'}} = -\frac{\mathbf{v}}{2}\Big[\kappa_{\mathbf{HHH}}\mathbf{H}^3 + \kappa_{\mathbf{HHH'}}\mathbf{s}_\theta\mathbf{H}^2\mathbf{H'} + \kappa_{\mathbf{HH'H'}}\mathbf{c}_\theta\mathbf{HH'}^2 + \kappa_{\mathbf{H'H'H'}}\mathbf{H'}^3\Big]$$

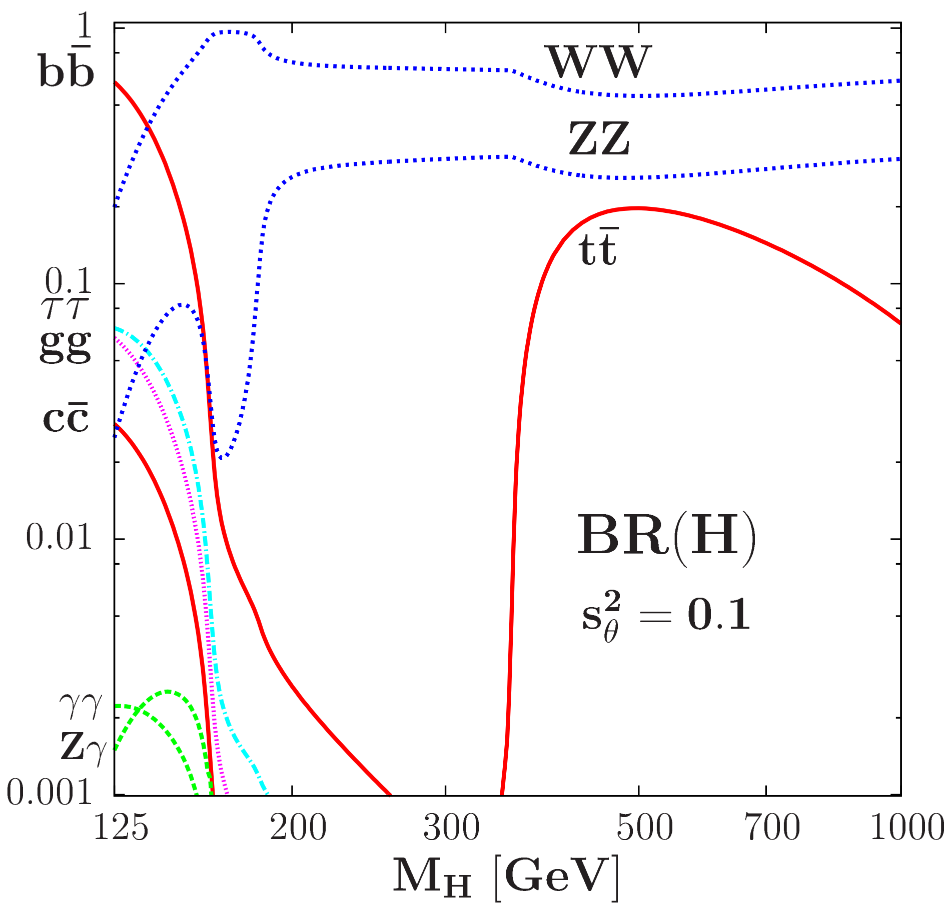
$$\kappa_{\mathbf{HHH}} = \frac{\mathbf{M_H^2}}{\mathbf{v}^2\mathbf{c}_\theta}\left(\mathbf{c}_\theta^4 - \mathbf{s}_\theta^2\frac{\lambda_{\mathbf{HH'}}\mathbf{v}^2}{\Delta\mathbf{M}^2_{\mathbf{HH'}}}\right),\ \kappa_{\mathbf{HHH'}} = \frac{2\mathbf{M_H^2}+\mathbf{M^2_{H'}}}{\mathbf{v}^2}\left(\mathbf{c}_\theta^2 + \frac{\lambda_{\mathbf{HH'}}\mathbf{v}^2}{\Delta\mathbf{M}^2}\right)$$

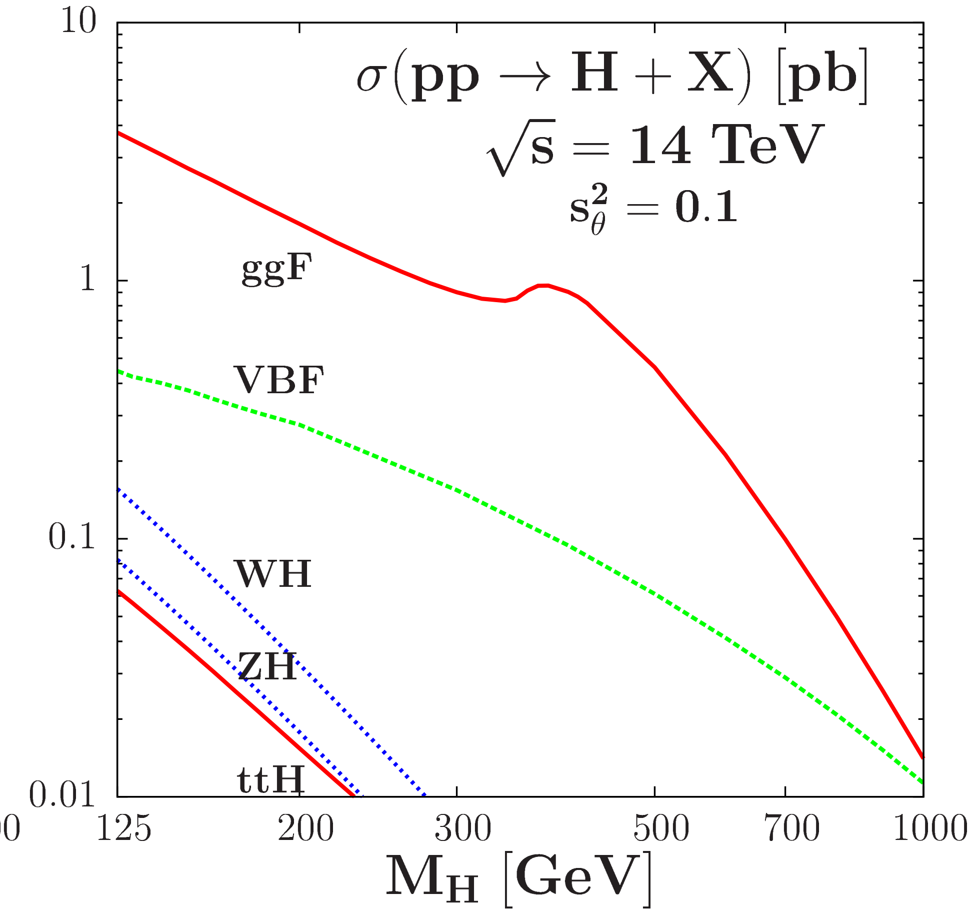
8. Simples extensions of the SM: singlets

$\equiv$ to SM Higgs case but with unknown mass and reduced couplings!

all theory information is available/discussed before for $M_H \neq 125$ GeV.

Branching ratios and cross sections as function of M_H for $\sin\theta = 0.1$.

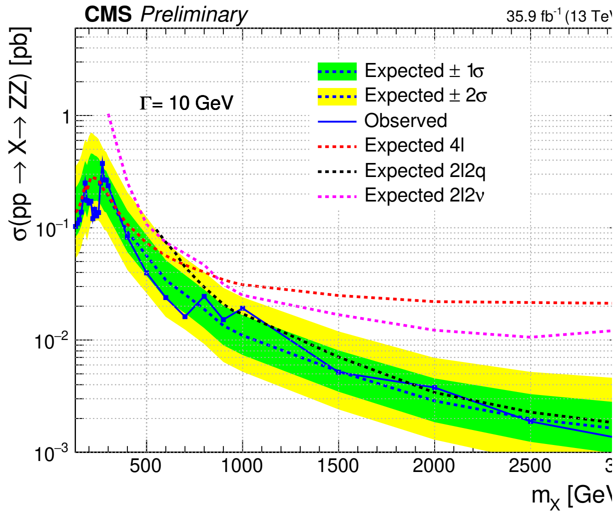


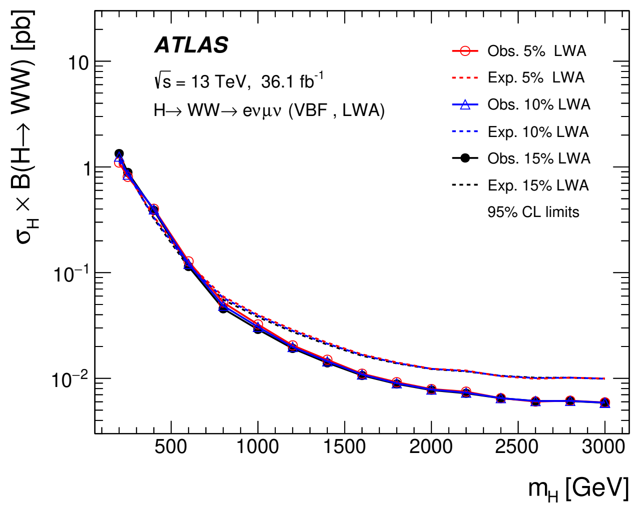


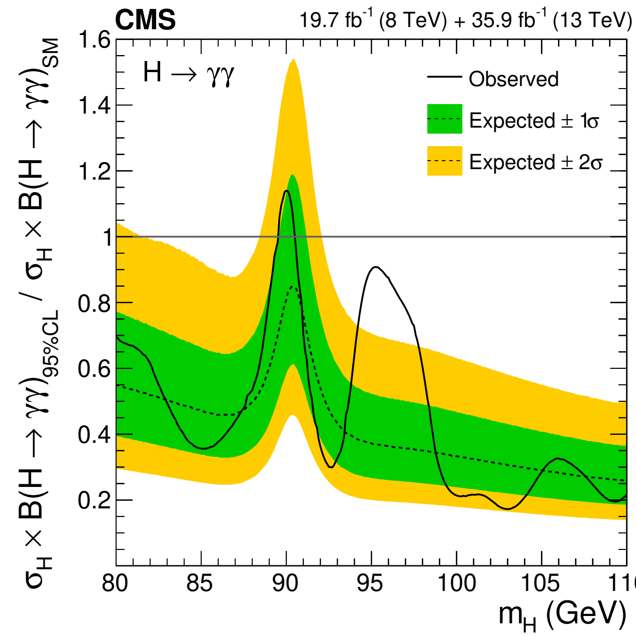
Exactly the same BR's but all σ's and the Γ_H^{tot} are reduced by $\sin^2\theta$.

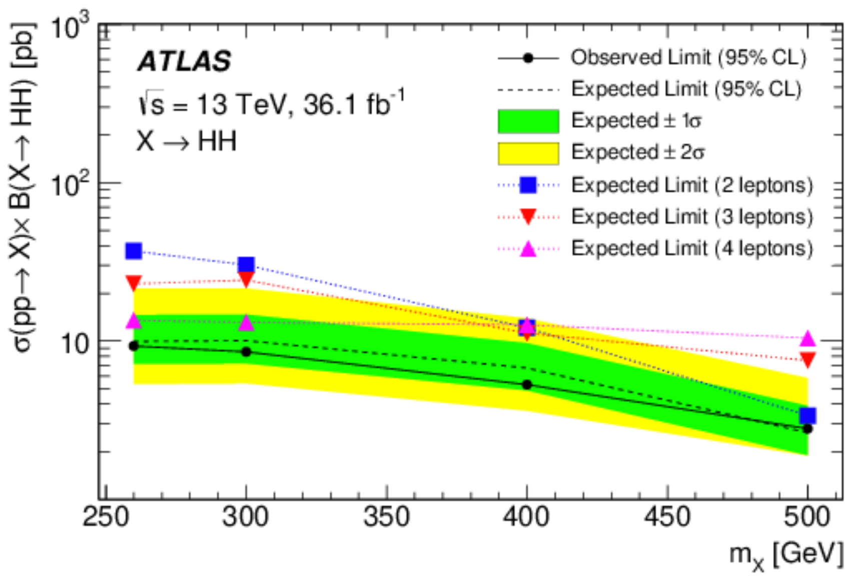
8. Simples extensions of the SM: singlets

Examples of $\rm H'$ searches: $\rm H' \to ZZ, WW, \gamma\gamma$ and $\rm H' \to HH$:









8. Simples extensions of the SM: Dark Matter

Including the Dark Matter is a must $\Rightarrow$ the SM Higgs-portal to DM.

A very simple DM description, using only Agnosticism and Occam razor:

postulate the existence of a weakly interacting massive particle:

- a singlet particle but of any spin i.e. a scalar, vector or fermion;
- Z_2 parity for stability: no couplings or mixing with fermions.
- QED neutral + isosinglet, no SU(2)xU(1) charge: no Z couplings;

Hence, only couplings with the Higgs bosons $\Rightarrow$ Higgs portal DM:

- annihilates into SM particles through s-channel Higgs exchange;
- interacts with fermionic matter only through Higgs exchange;
- can be produced in pairs via Higgs boson exchange or decays.

Again Occam razor: assume only the SM-like Higgs boson.

Then use an effective Lagrangian, but the simplest (renormalizable?) one:

$$\Delta\mathcal{L}_s = -\frac{1}{2}M_s^2 s^2 - \frac{1}{4}\lambda_s s^4 - \frac{1}{4}\lambda_{Hss}\Phi^\dagger\Phi s^2$$

$$\Delta\mathcal{L}_v = \frac{1}{2}M_v^2 v_\mu v^\mu + \frac{1}{4}\lambda_v (v_\mu v^\mu)^2 + \frac{1}{4}\lambda_{Hvv}\Phi^\dagger\Phi v_\mu v^\mu$$

$$\Delta\mathcal{L}_\chi = -\frac{1}{2}M_\chi \bar\chi\chi - \frac{1}{4}\frac{\lambda_{H\chi\chi}}{\Lambda}\Phi^\dagger\Phi\bar\chi\chi$$

Mc Donald

Kanemura, ...

Lebedev,AD, ..

EWSB: $\Phi \to \frac{1}{\sqrt{2}}(v+H)$ with v=246 GeV and $m_x^2 = M_x^2 + \frac{1}{4}\lambda_{Hxx}v^2$ ...

Only two free parameters: DM mass m_x and DM-Higgs coupling λ_{Hxx}

8. Simples extensions of the SM: Dark Matter

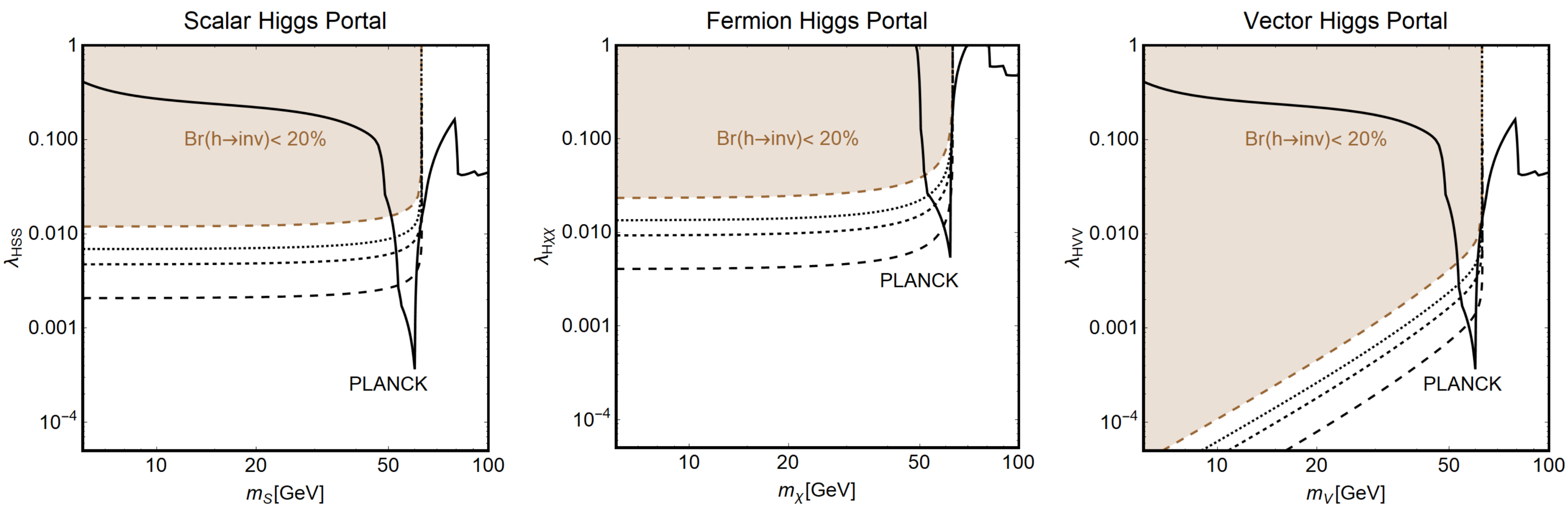
For light DM states, only possible handle at colliders is Higgs decays:

$$\Gamma_{\rm inv}(H \to ss) = \frac{\lambda^2_{Hss} v^2 \beta_s}{64\pi M_H}$$

$$\Gamma_{\rm inv}(H \to vv) = \frac{\lambda^2_{Hvv} v^2 M_H^3 \beta_v}{256\pi M_v^4}\left(1 - 4\frac{M_v^2}{M_H^2} + 12\frac{M_v^4}{M_H^4}\right)$$

$$\Gamma_{\rm inv}(H \to ff) = \frac{\lambda^2_{Hff} v^2 M_H \beta_f^3}{32\pi \Lambda^2}$$

Possible only for $m_X < \frac{1}{2} M_H \approx 62$ GeV; depends on m_X, λ_{HXX}:

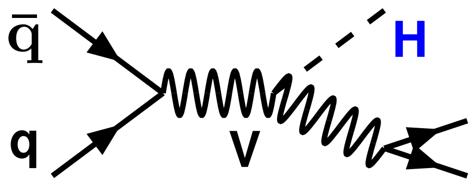


One has to check also the relic density/Planck: only one input?

maybe no, X does not form all DM and/or Ωh^2 obtained via other means...

8. Simples extensions of the SM: Dark Matter

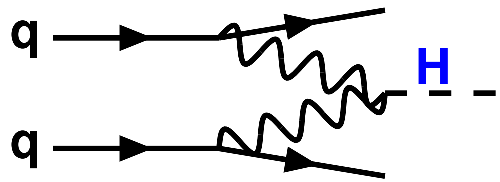
- **Direct: measurement of total Higgs decay width via interference.**
- **Indirect: measurements of the Higgs decay branching ratios.**
- **Even more direct: search for Higgs decaying invisibly and $E\!\!\!/_T$**



$q\bar{q} \to WH \to \ell\nu + E\!\!\!/_T$

$q\bar{q} \to ZH \to \ell\ell + E\!\!\!/_T$

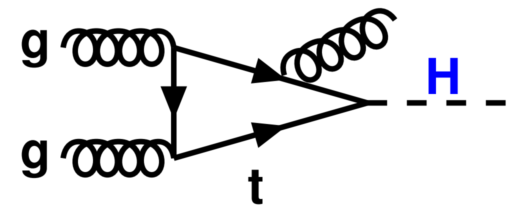
Choudhury+Roy, ...,



$qq \to qqH \to jj + E\!\!\!/_T$

high-mass, p_T, η jets

Eboli+Zeppenfeld

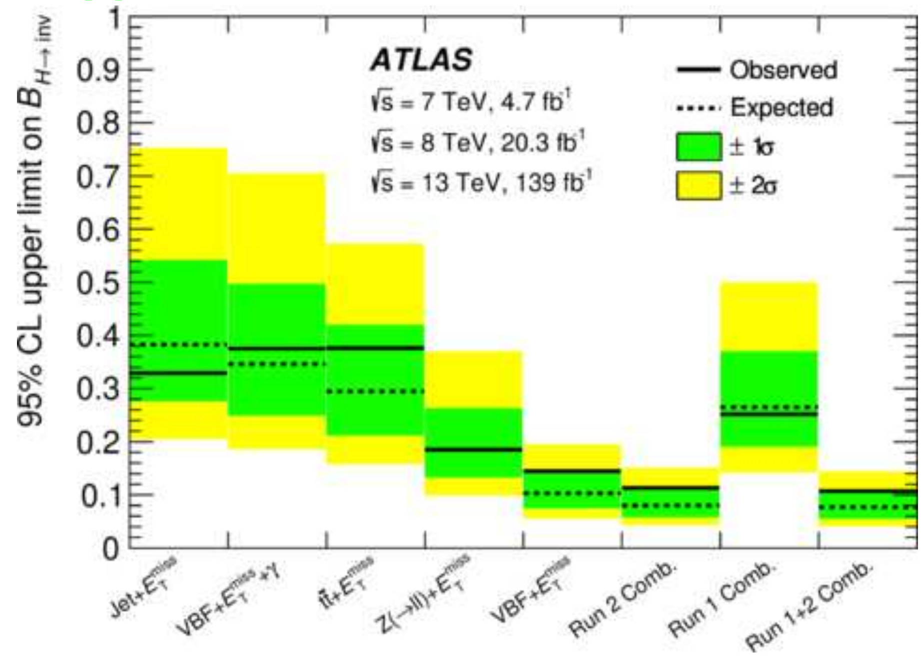


$gg \to Hg \to j + E\!\!\!/_T$

also 2j, high rate.

AD,Falkowski,Mambrini...

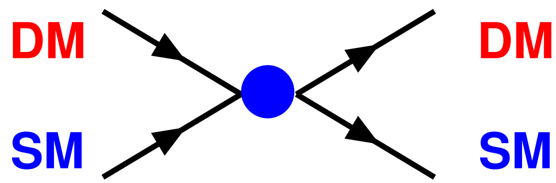
Combining all the search channels in ATLAS gives
BR(H→inv) $\lesssim 0.093$



8. Simples extensions of the SM: Dark Matter

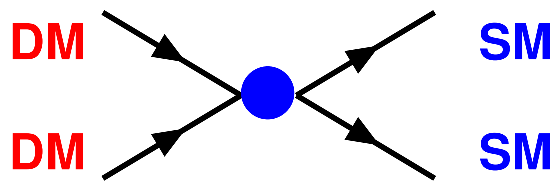
Results can be compared with those of Astroparticle physics experiments.

Direct detection:



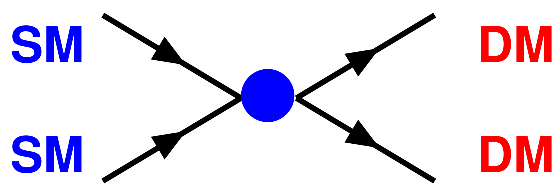
scattering on nucl. target:
XENON $\Rightarrow$ LZ,DARWIN

Indirect detection:

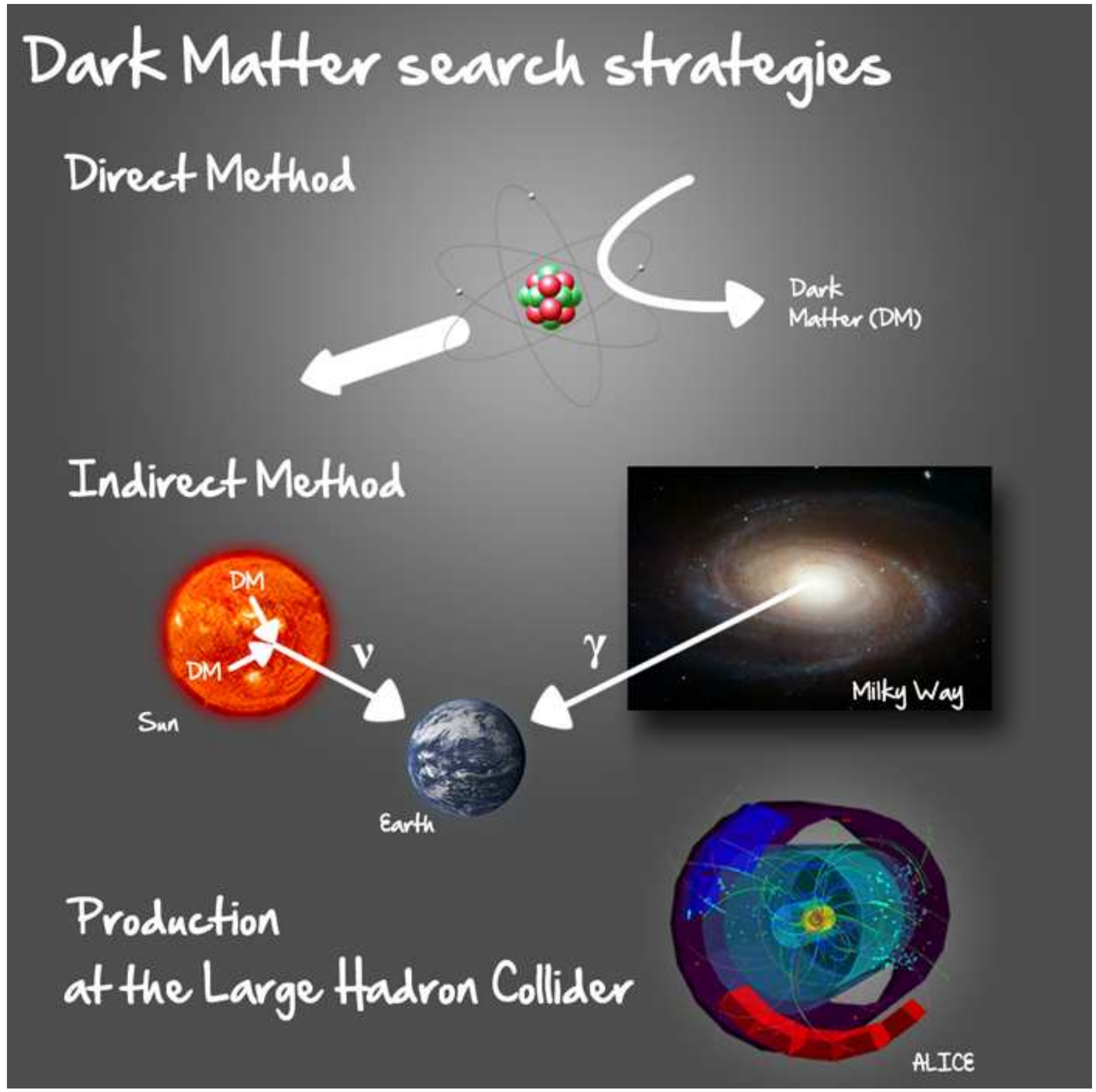


annihilation products:γ, ν
HESS,Fermi$\Rightarrow$ CTA, ...

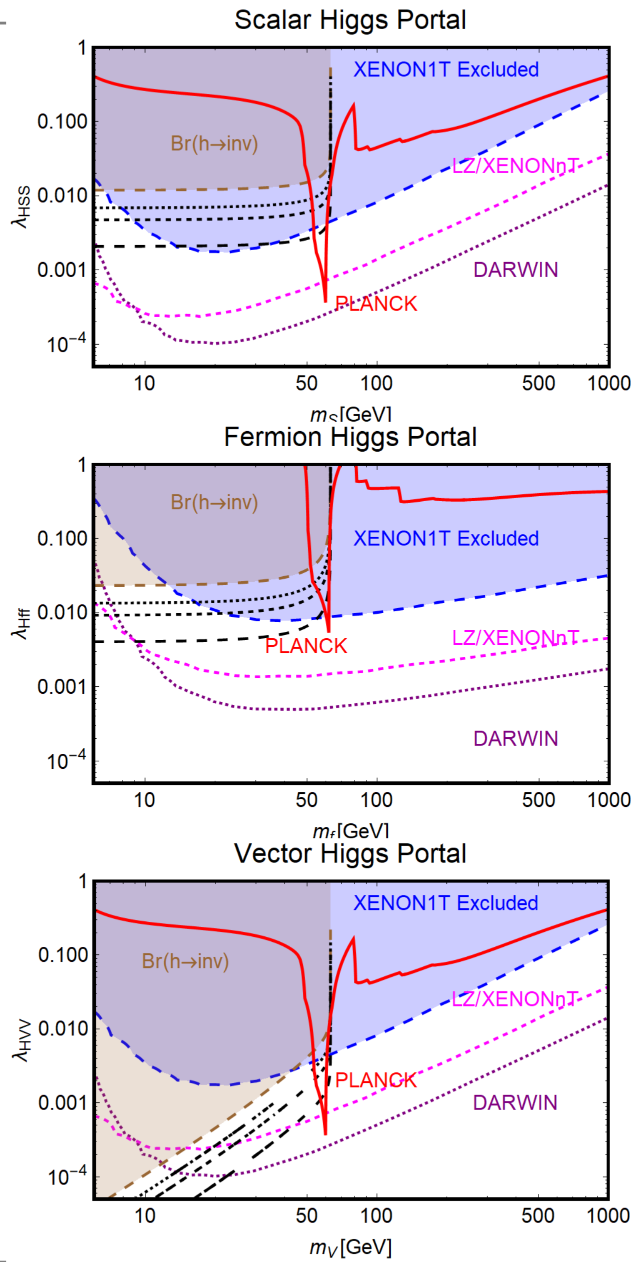
Detection at colliders:

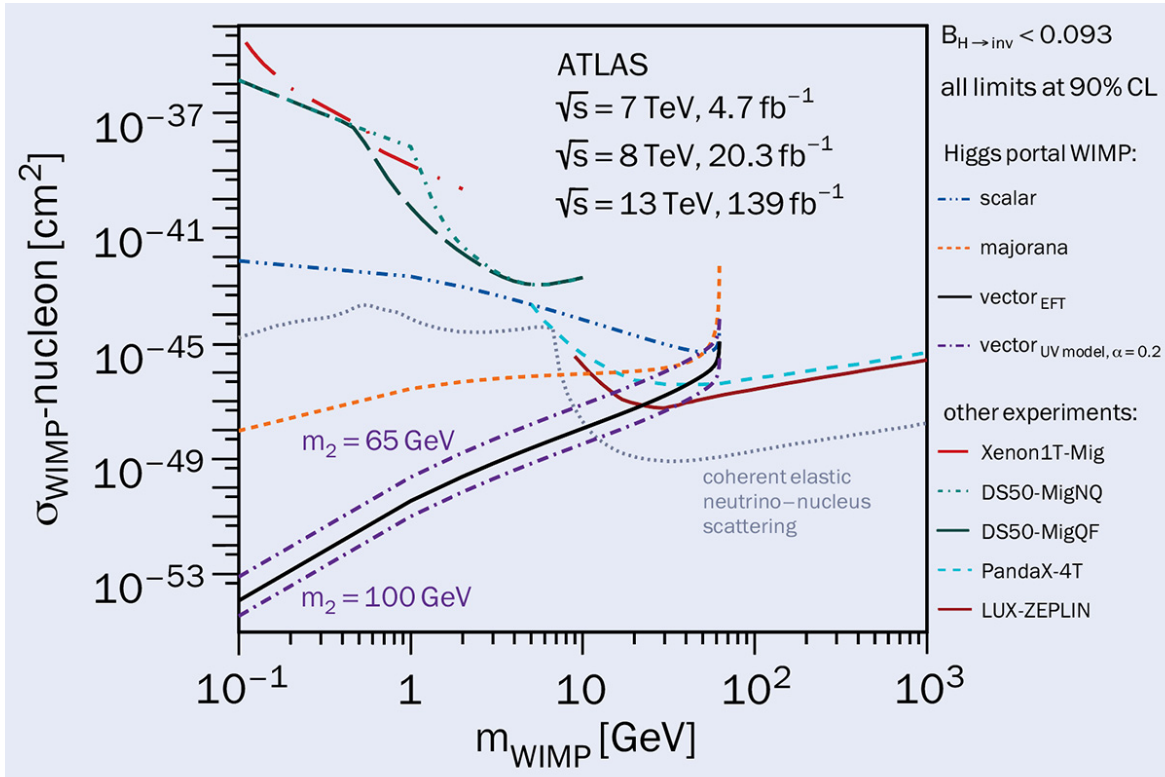


missing energy signature
LHC $\Rightarrow$ HL-LHC,e^+e^-,pp



8. Simples extensions of the SM: Dark Matter





9. The Higgs sector of the MSSM

Supersymmetry: symmetry relating fermions s=$\frac{1}{2}$ and bosons s=0,1.

– a new sparticle for each SM particle, with spin different by unit $\frac{1}{2}$;

– as seen, beautiful: most general, link to gravity and superstrings,....

– solves SM pbs: hierarchy, unification, Dark Matter (+$\not{P}$,m$_\nu$,Bgenesis..).

– however, SUSY must be broken $\Rightarrow$ effective way at low energy?

Focus on: **Minimal Supersymmetric Standard Model (MSSM):**

- minimal gauge group: the SM one, SU(3)$\times$SU(2)$\times$U(1);
- minimal particle content: 3 fermion families and 2 Φ doublets,

– to cancel the chiral anomalies introduced by the new SUSY $\tilde{\rm h}$ field,

– give separately masses to d and u fermions in SUSY invariant way.

- R=$(-1)^{(2\rm s+L+3B)}$ parity is conserved; LSP is stable;
- minimal set of terms (masses, couplings) breaking "softly" SUSY.

To reduce the number of the (too many in general) free parameters:

– impose phenomenological constraints: O(20) free parameters,

– in general sparticles assumed to be heavy: decouple from Higgs.

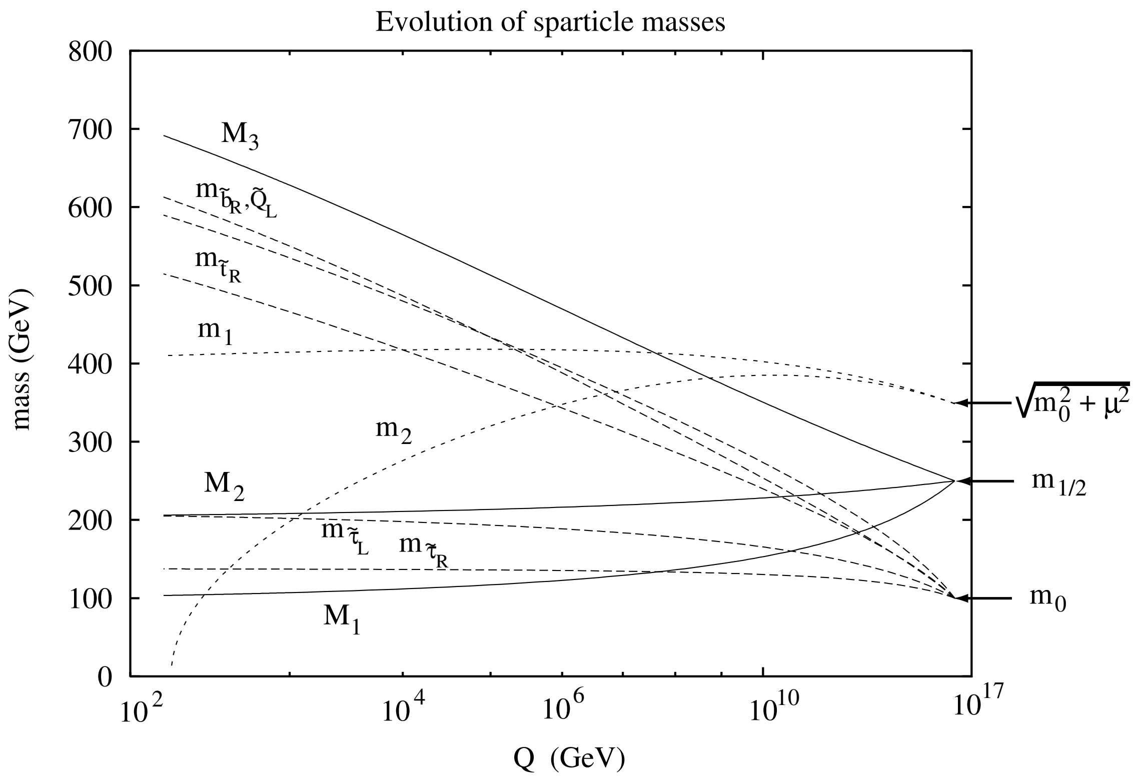
– constrained models with universal boundaries, very few parameters

9. The Higgs sector of the MSSM

mSUGRA: at GUT scale, only 4.5 param: $\tan\beta, m_{1/2}, m_0, A_0, \text{sign}(\mu)$

All soft SUSY-breaking parameters at scale M_S are obtained through RGEs.

With $M_{GUT} \sim 2 \cdot 10^{16}$ GeV and $M_{SUSY} \sim \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$, one then gets:



Radiative EWSB occurs since $M^2_{H_2} < 0$ at a scale M_Z $(t/\tilde{t}$ loops),

$\Rightarrow$ EWSB is more natural in the MSSM ($\mu^2 < 0$ from RGEs) than in SM!

9. The Higgs sector of the MSSM

In MSSM with two Higgs doublets: $H_1 = \binom{H_1^0}{H_1^-}$ and $H_2 = \binom{H_2^+}{H_2^0}$,

After EWSB, 3dof make $W_L^\pm, Z_L \Rightarrow$ 5 physical states left: $h, H, A, H^\pm$

Only two free parameters at the tree level: $\tan\beta = v_2/v_1, M_A$; others:

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

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

$$\tan 2\alpha = \tan 2\beta\,(M_A^2+M_Z^2)/(M_A^2-M_Z^2)$$

We have important SUSY constraint on the MSSM Higgs boson masses:

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

$M_A \gg M_Z$: decoupling regime, all Higgses heavy except for h.

$$M_h \sim M_Z|\cos 2\beta| \leq M_Z!\ ,\ M_H \sim M_{H^\pm} \sim M_A\ ,\ \alpha \sim \frac{\pi}{2} - \beta$$

The radiative corrections are very important in the MSSM Higgs sector.

- Dominant corrections are due to the top (s)quark at one-loop level:

$\Delta M_h^2 = \frac{3g^2}{2\pi^2}\frac{m_t^4}{M_W^2}\log\frac{m_{\tilde t}^2}{m_t^2}$ large: $M_h^{max} \to M_Z + 35\,\text{GeV} \gtrsim 125\,\text{GeV}$

Needs large values of $M_S, M_A, \tan\beta$ and A_t.

9. The Higgs sector of the MSSM

Higgs decays and cross sections strongly depend on couplings.

The couplings in terms of $\mathrm{H_{SM}}$ and their values in decoupling limit:

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

– **The couplings of $\mathrm{H^{\pm}}$ have the same intensity as those of A.**

– **Couplings of $\mathrm{h, H}$ to VV are suppressed; no AVV couplings (CP).**

– **For $\tan\beta > 1$: couplings to d enhanced, couplings to u suppressed.**

– **For $\tan\beta \gg 1$: couplings to b quarks ($\mathrm{m_b}\tan\beta$) very strong.**

– **For $\mathrm{M_A \gg M_Z}$: h couples like the SM Higgs boson and H like A.**

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

Radiative corrections included in hMSSM way: traded with $\mathrm{M_h}$=125 GeV:

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

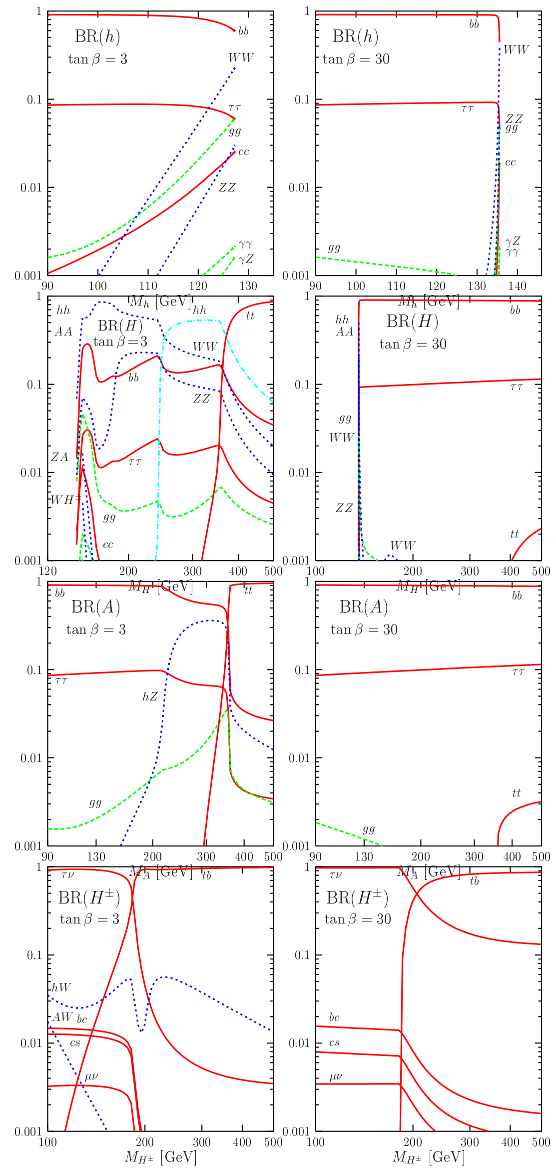
9. The Higgs sector of the MSSM

Decays of the MSSM Higgs bosons, a brief and general survey:

- h: **same decays as $\mathrm{H_{SM}}$ in general (esp. in decoupling limit); if not $\mathrm{h \to b\bar{b}}, \tau^+\tau^-$ enhanced for tanβ >1**
- A: **only $\mathrm{b\bar{b}}, \tau^+\tau^-$ and $\mathrm{t\bar{t}}$ decays (no VV decays, $\mathrm{A \to hZ}$ suppressed).**
- H: **same as A in general; tan$\beta \gg$1 WW, ZZ, hh decays but suppressed.**
- $\mathrm{H^{\pm}}$ **mainly $\tau\nu$ and tb decays (depending if $\mathrm{M_{H^{\pm}}} <$ or $> \mathrm{m_t}$).**

Possible new effects from SUSY!!

In particular, invisible h,H,A decays



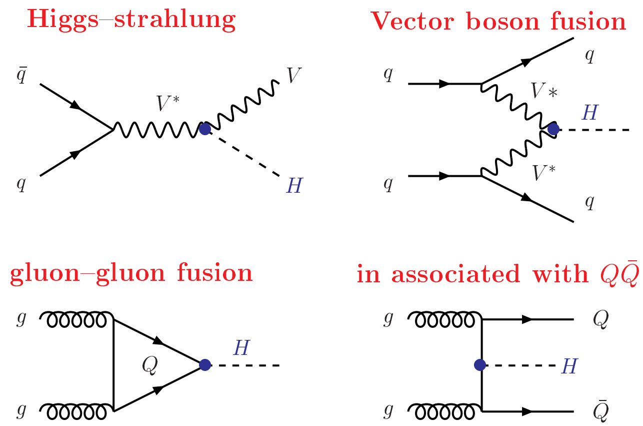
For tan$\beta \gg$1, only decays into b/τ:

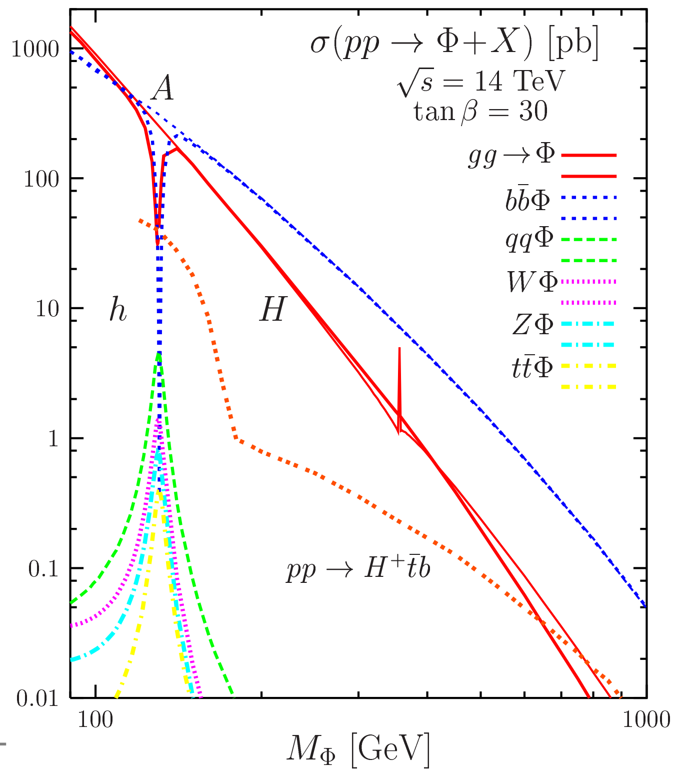
BR: $\Phi \to \mathrm{b\bar{b}} \approx 90\%$, $\Phi \to \tau\tau \approx 10\%$

For tan$\beta \approx$1, many other decay channels!

9. The Higgs sector of the MSSM

SM production mechanisms





What is different in the MSSM

- All work for CP–even h,H bosons.

– in ΦV, $qq\Phi$ h/H complementary

– $\sigma(h) + \sigma(H) = \sigma(H_{SM})$

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

- For $gg \to \Phi$ and $pp \to tt\Phi$

– include the b–quarks contribution

– dominant one at high tanβ values.

- 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 $pp \to t\bar{b}H^-$

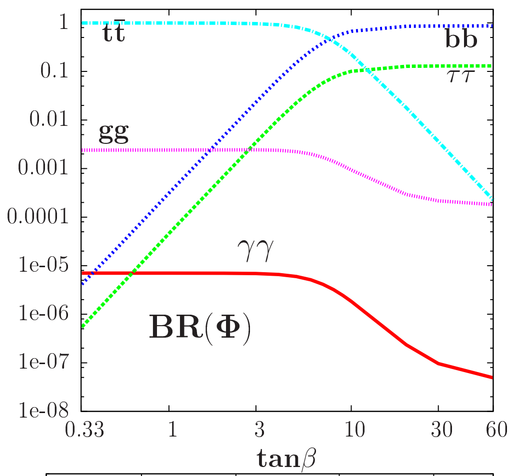
Radiative corrections important again

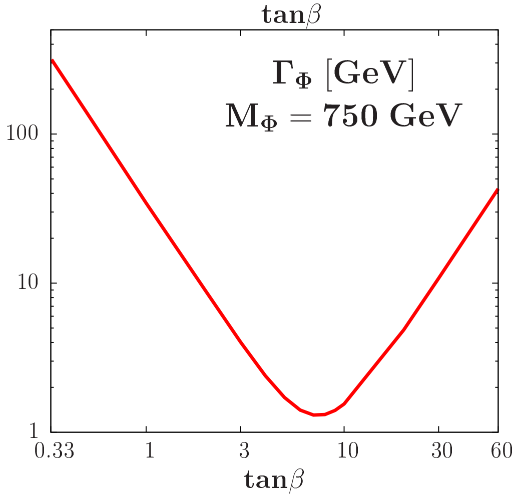
$gg \to H/A$ (available only at NLO)

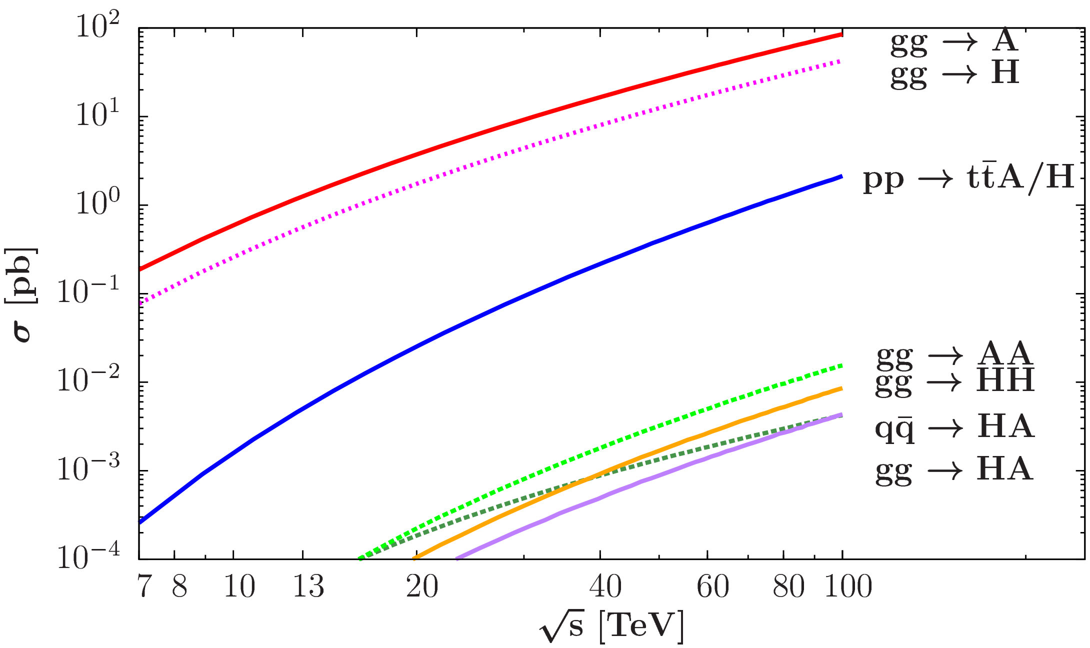
$bb \to H/A$ are rather large (K≈1.5).

9. The Higgs sector of the MSSM

Phenomenology of MSSM Higgs similar to that of general 2HDM proviso:
- the 2HDM is of Type-II: H_1 couples to u-quarks/V bosons and H_2 to d;
- the lighter h state has M_h=125 GeV and SM-like couplings at 10% level;
- we are in the alignment (=decoupling) limit in which $\sin(\beta-\alpha)\to 1$;
- the heavy H/A/$H^\pm$ states are degenerate in mass: $M_H \approx M_{H^\pm} \approx M_A$.







Production for tanβ=1 and $M_H = M_A$

9. The Higgs sector of the MSSM

Most constraining searches are exactly those of 2HDM in alignment limit:

$pp \to gg/b\bar{b} \to H/A \to \tau^+\tau^-$

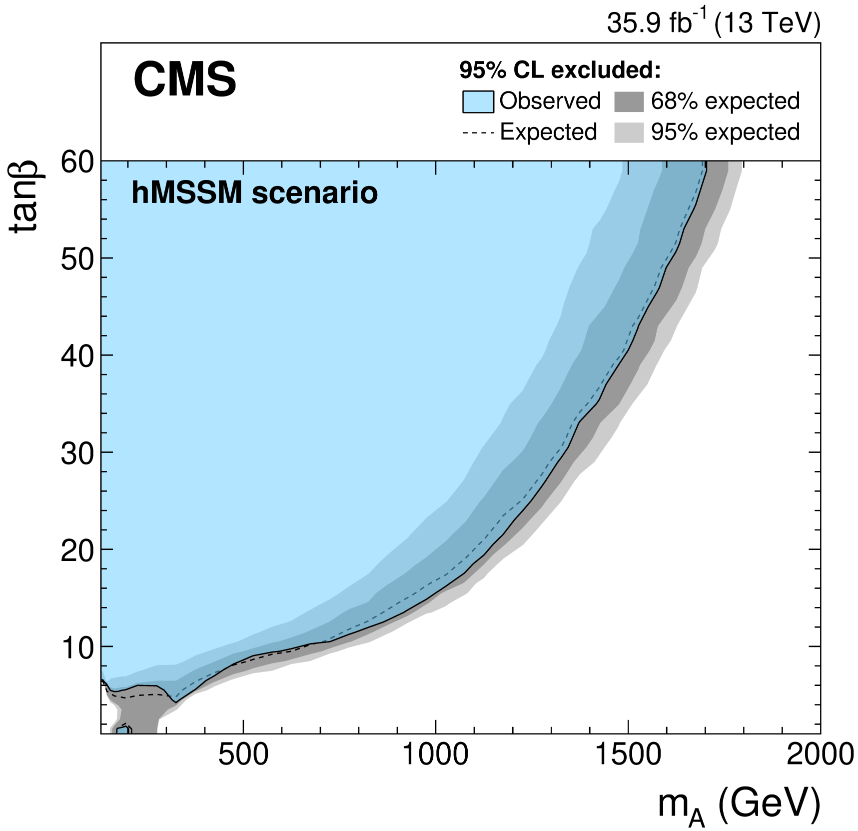
Strong constraints on space!

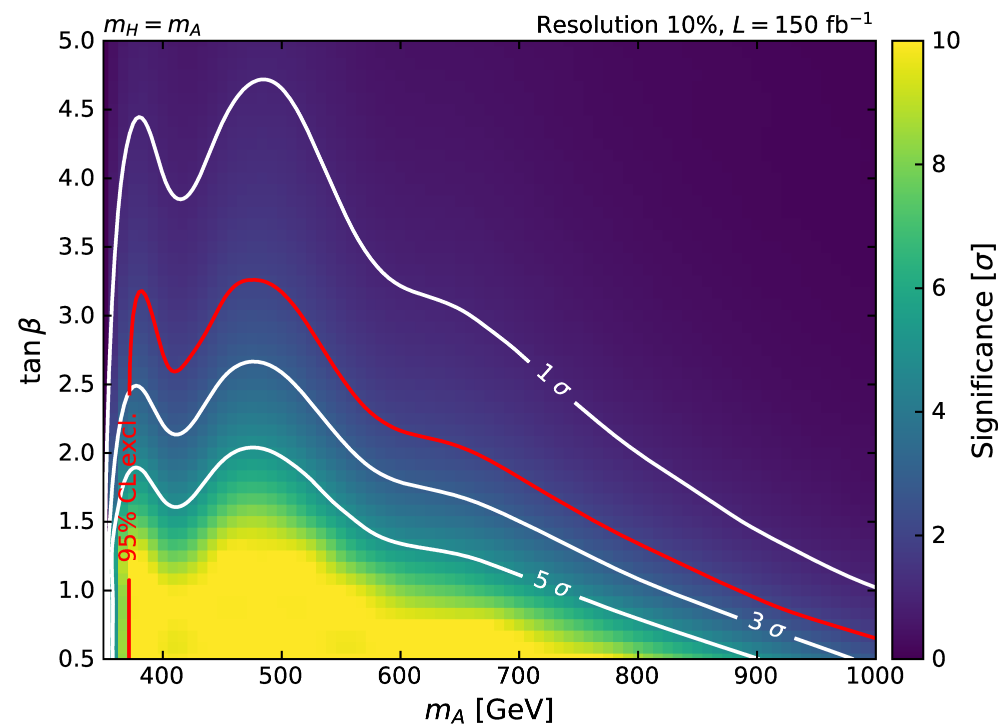
$M_A = M_H > 1$ **TeV if tan**β $<$**10.**

$pp \to gg/q\bar{q} \to H/A \to t\bar{t}$

Interference with QCD $gg \to t\bar{t}$

Very low tanβ **values excluded.**





9. The Higgs sector of the MSSM

For the charged Higgs, searches are exactly those of 2HDM Type II:

Main production channel is:

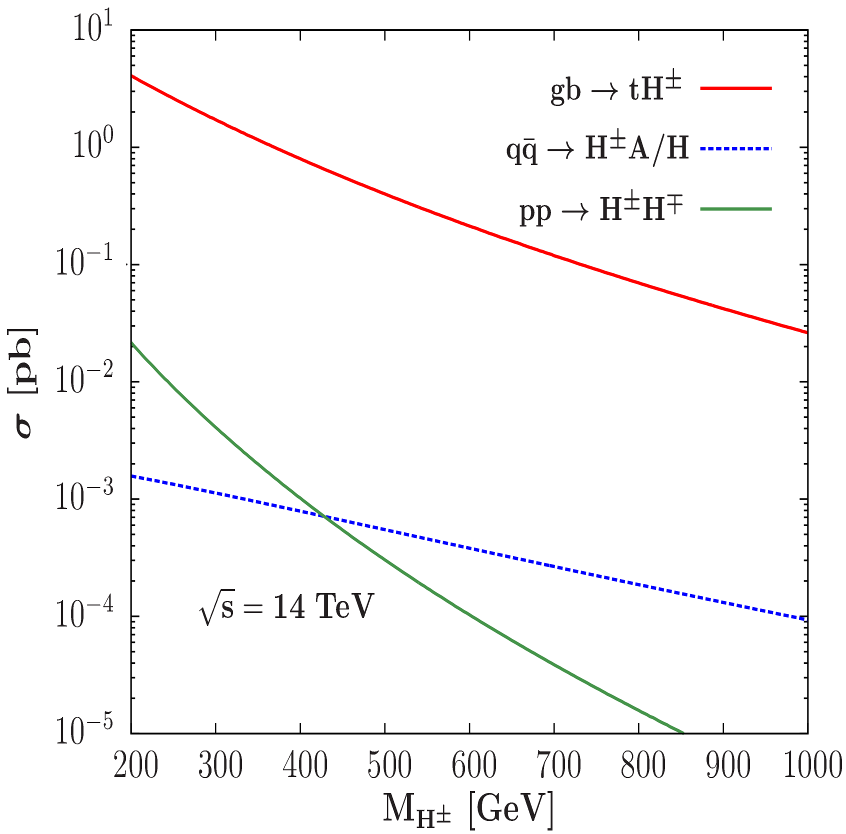
$pp \to gg \to btH^{\pm}$ $(gb \to tH^{+})$

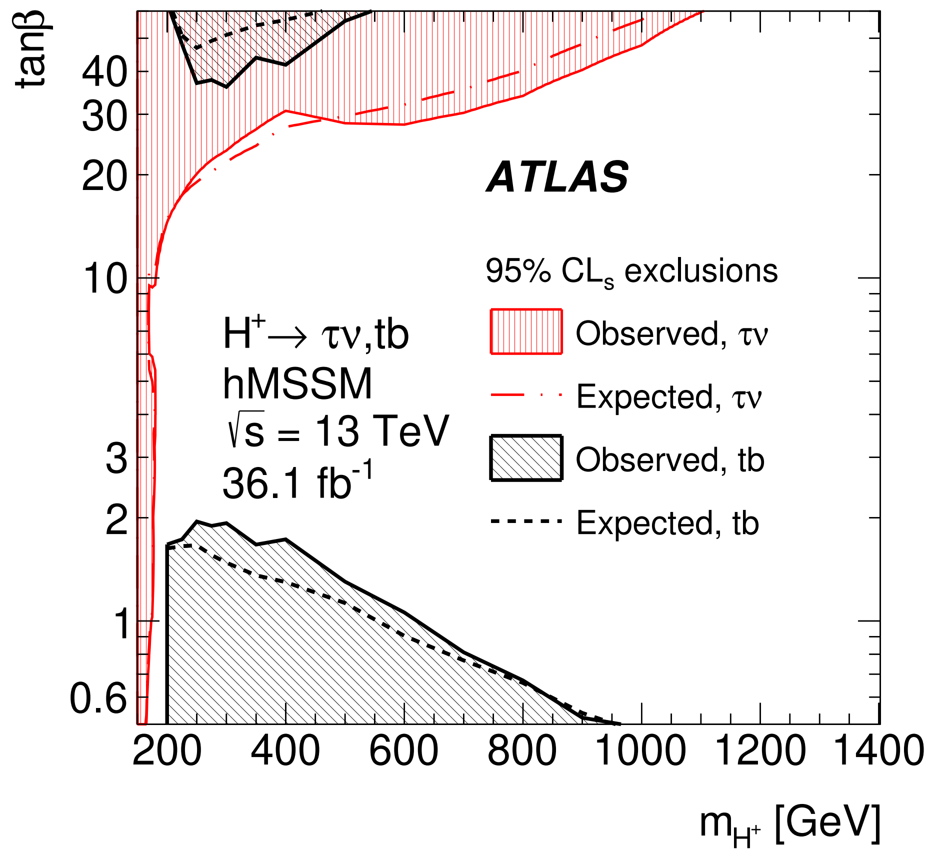
Other channels are subleading.

Main search topologies:

$H^{+} \to \tau^{+}\nu$ **and** $H^{+} \to t\bar{b}$

High and low tanβ excluded.

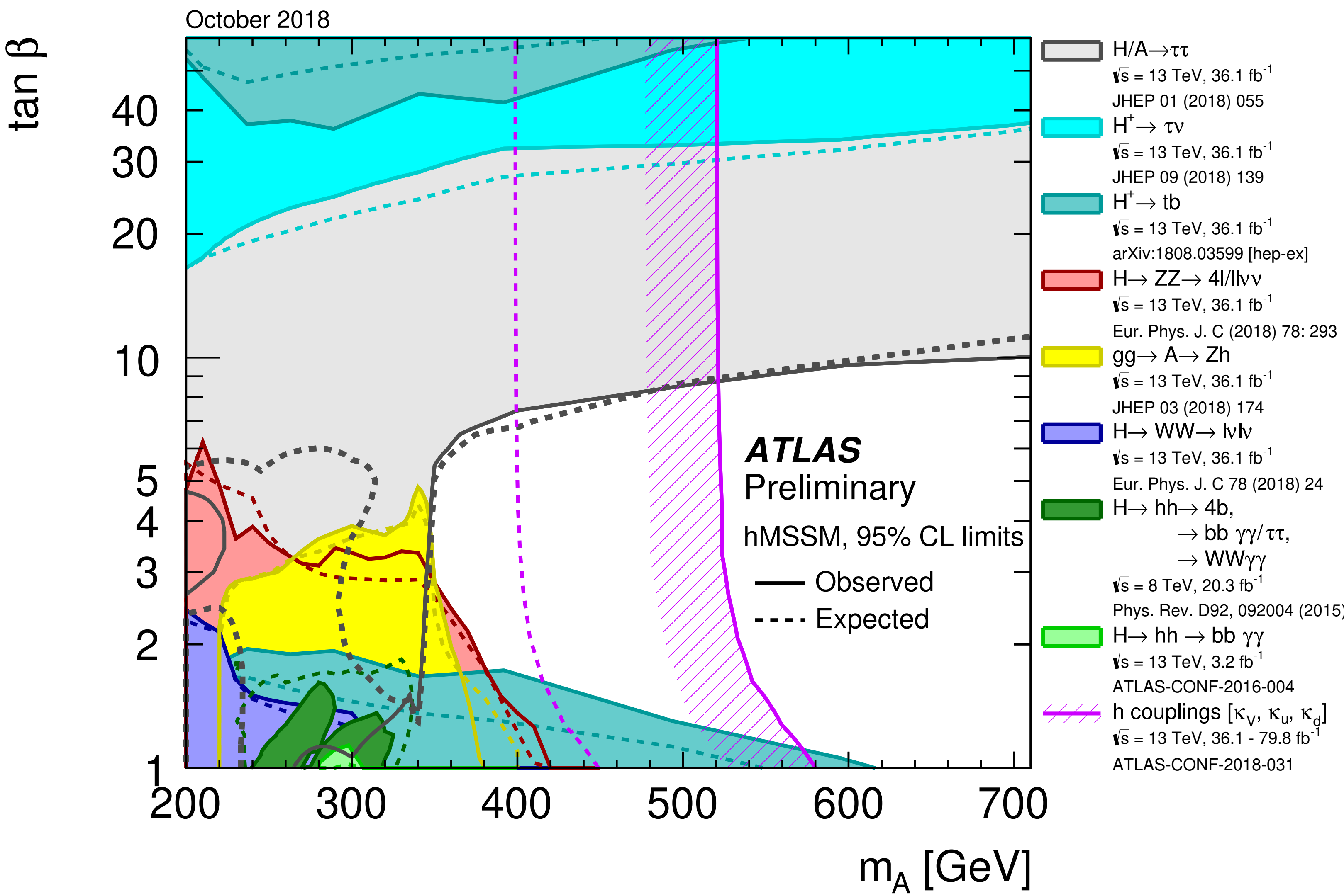




9. The Higgs sector of the MSSM

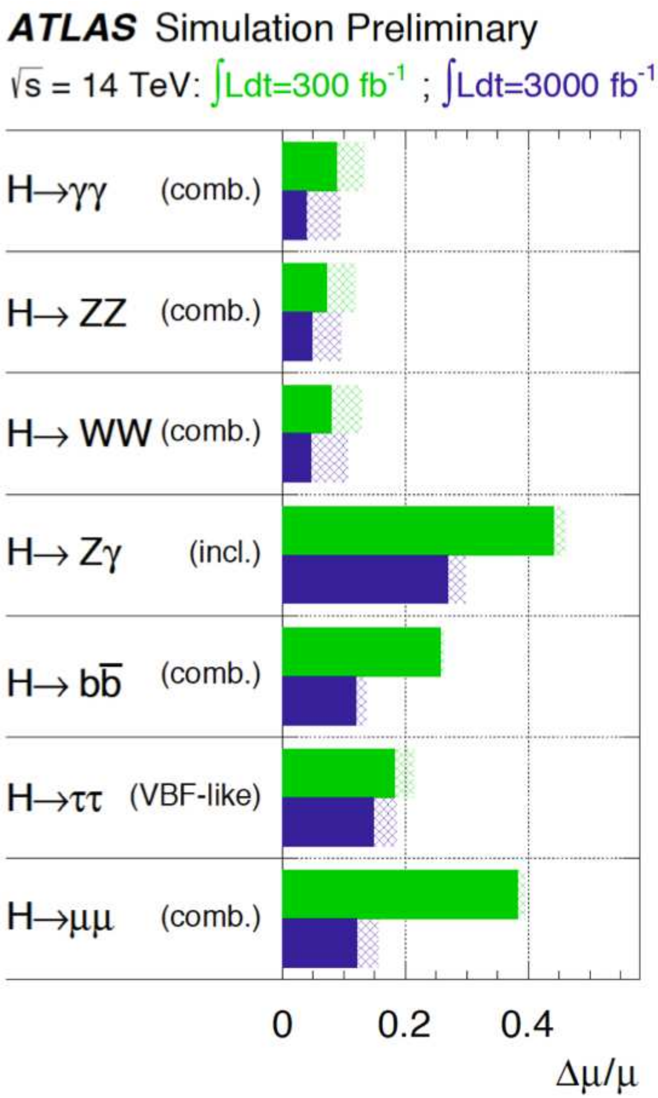
But one should include all channels for H,A,H$^{\pm}$ production and decays:

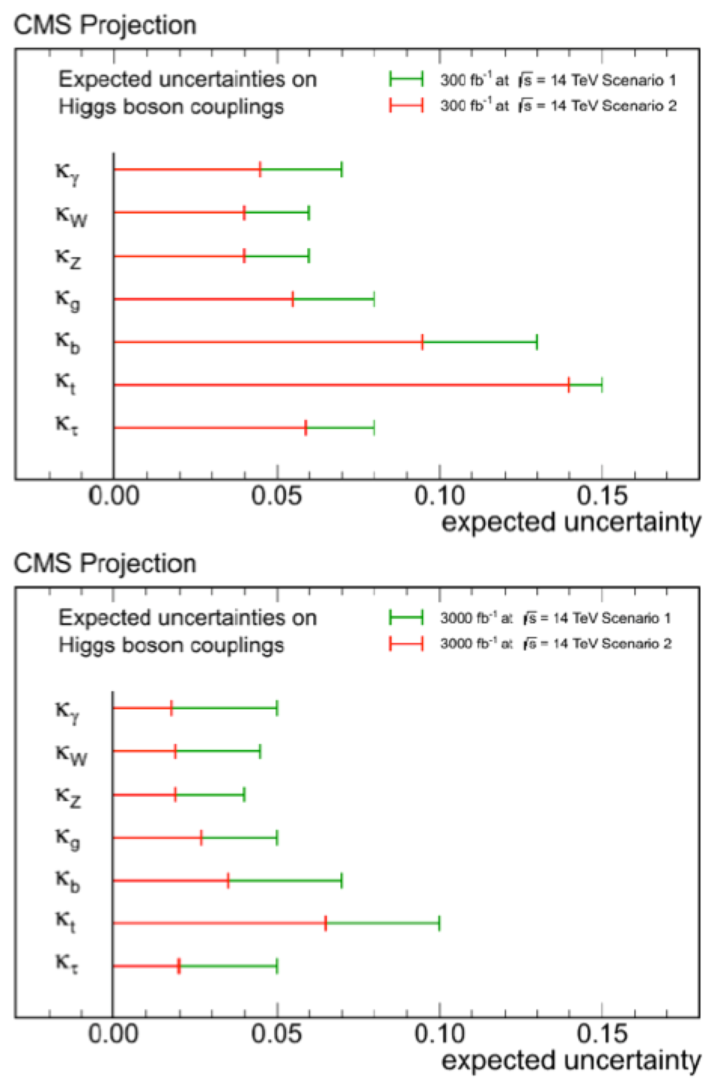
$\mathbf{A \to hZ,\ H \to WW, ZZ, \gamma\gamma, hh,\ H^{\pm} \to hW}$ **etc.. and indirect bounds?**



10. Outlook

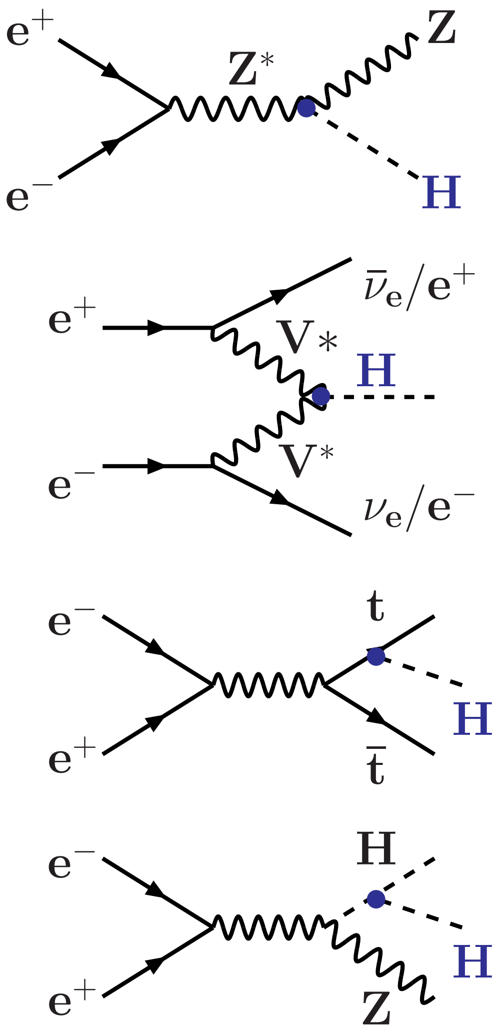
All these tests should be pursued at the high-luminosity LHC (HL-LHC):
much stronger constraints to be obtained; a factor 2–3 better is expected.

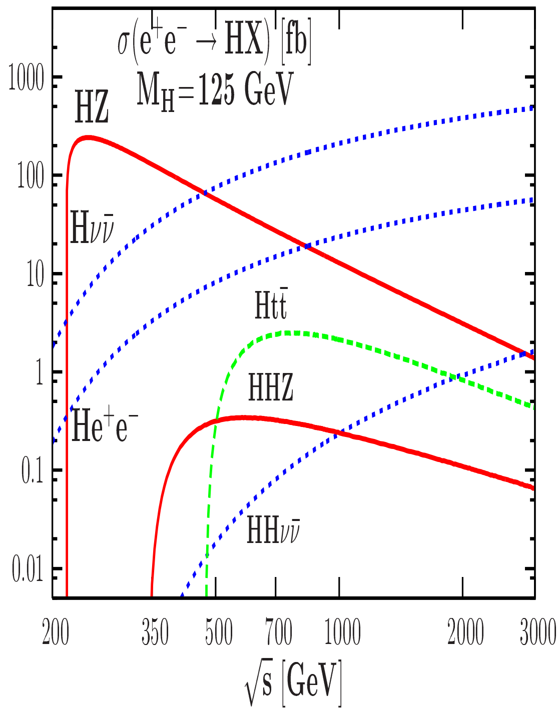




10. Outlook

The SM-like Higgs profile can be better determined at ILC, FCC-ee, ...





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

ILC in 2010 $\Rightarrow$

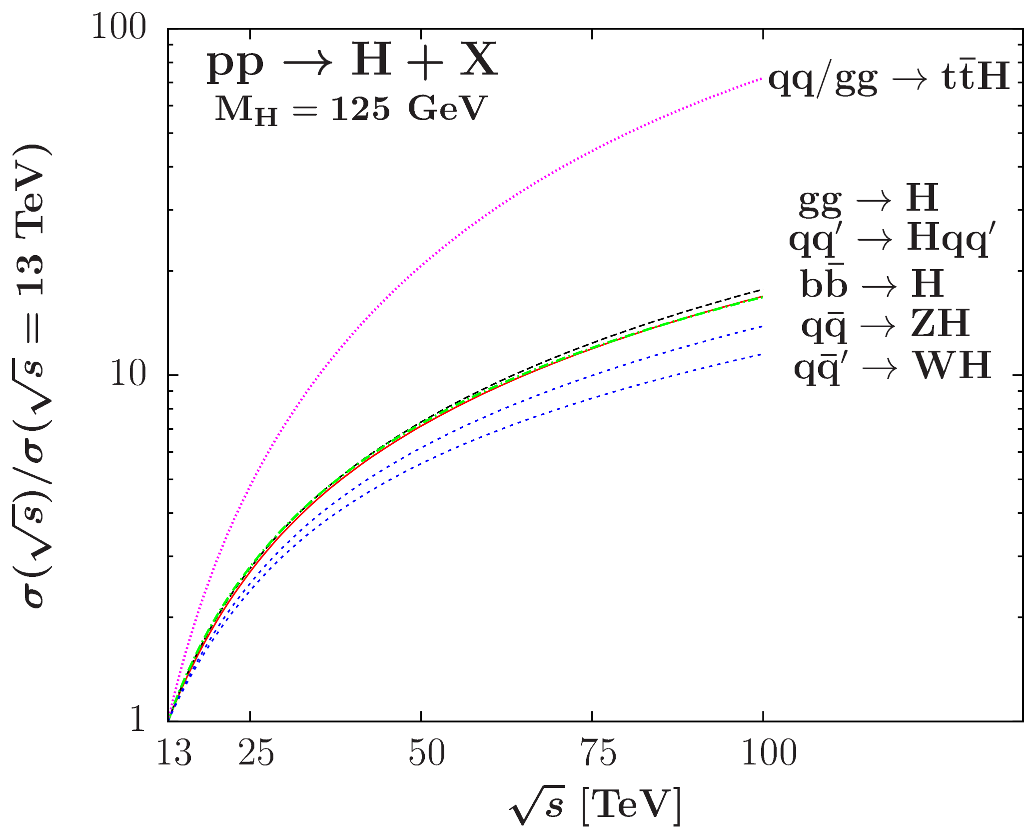
g_{HWW}	± 0.012
g_{HZZ}	± 0.012
g_{Hbb}	± 0.022
g_{Hcc}	± 0.037
$g_{H\tau\tau}$	± 0.033
g_{Htt}	± 0.030
λ_{HHH}	± 0.22
M_H	± 0.0004
Γ_H	± 0.061
CP	± 0.038

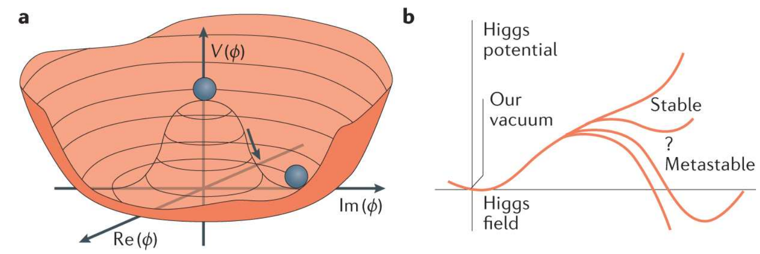
$\Rightarrow$ difficult to be beaten by anything else for a $\approx$ 125 GeV Higgs

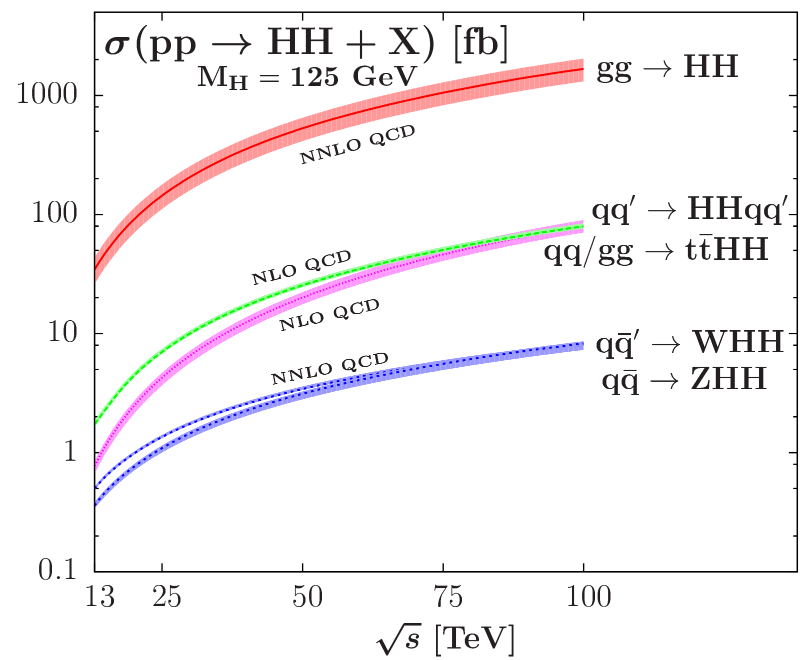
$\Rightarrow$ welcome to the e^+e^- precision machine!

10. Outlook

An important step could be reached by going to higher energy (FCC-pp ?):
much stronger constraints on H properties and access to self-coupling:







10. Outlook

Direct searches too should be pursued at HL-LHC+beyond (FCC-pp, μ-C?): much stronger constraints on parameter space to be obtained; ex in MSSM:

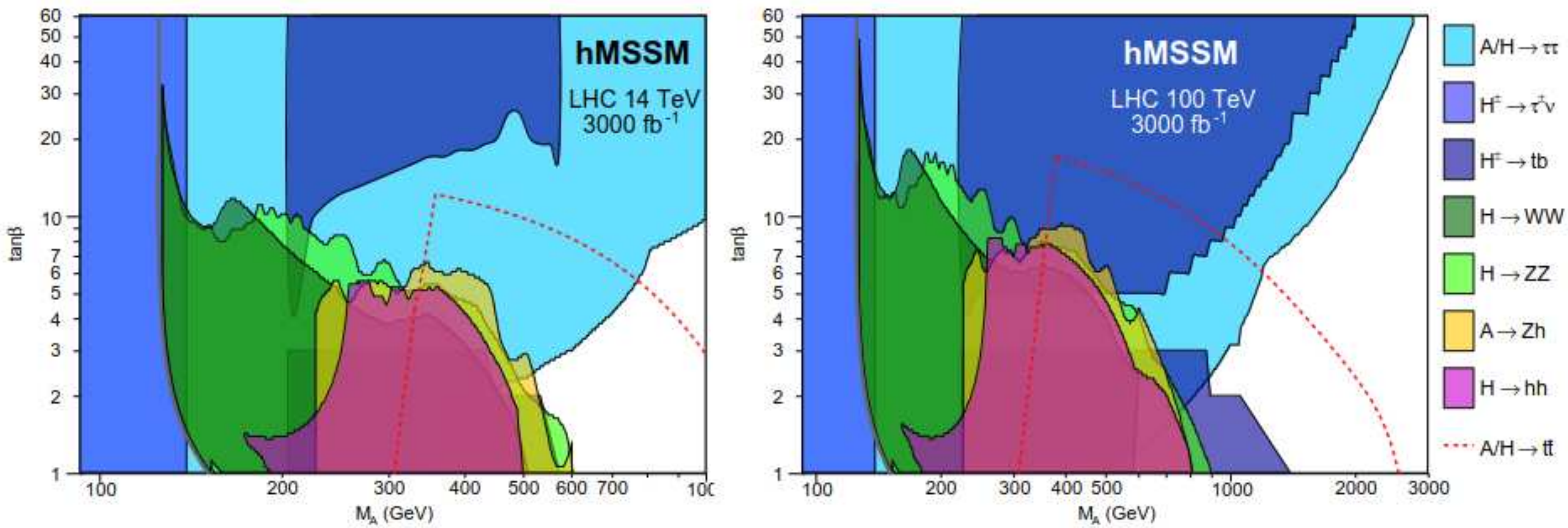


Figure 94: Top: 95%CL countours in the hMSSM $[\tan\beta, M_A]$ plane when the ATLAS and CMS searches for $A/H/H^{\pm}$ states in the various modes (specified in the figure with the corresponding color) at RunI are combined. Bottom: the projected 2σ sensitivity at HL–LHC with $\sqrt{s} = 14$ TeV (left) and at a $\sqrt{s} = 100$ TeV collider with 3 ab^{-1} data (right) are also shown assuming that it scales simply with the number of events; from [422].

And, if we are lucky, some sign of beyond the SM would finally show up.

10. Outlook

I always like to finish with this slide (since 10 years and is still valid)...

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 <u>at the end</u> we finally understand the EWSB mechanism. But there is a long way until then, and there might be many surprises.

We should keep going!