Higgs Phenomenology

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1. EWSB in the SM

Recapitaulation of what has been said by Profs. Barroso and Haber

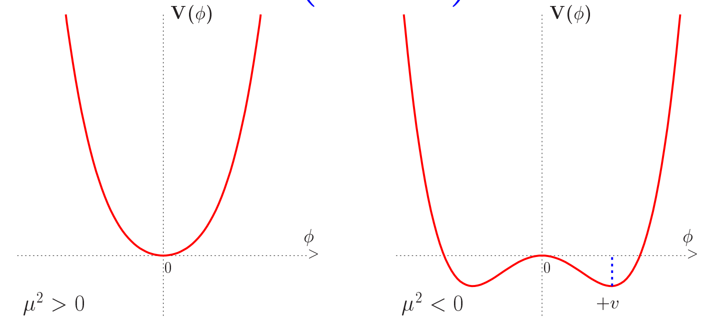
In the SM, if gauge boson and fermion masses are put by hand in $\mathcal{L}_{\rm SM}$

breaking of gauge symmetry $\Rightarrow$ spontaneous EW symmetry breaking

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

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

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

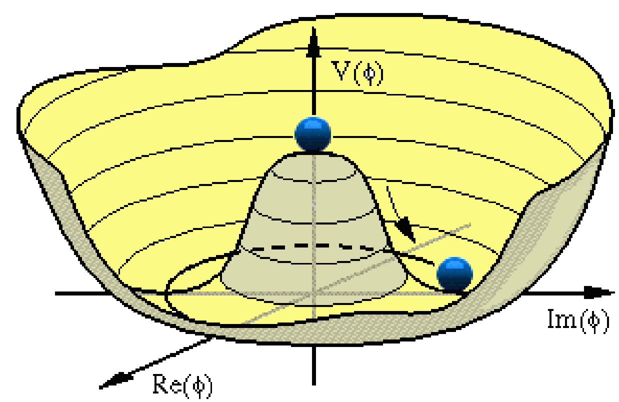


$\mu^2 > 0$: **4 scalar particles.**

$\mu^2 < 0$: Φ **develops a vev:**

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

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



To obtain the physical states,
write $\mathcal{L}_S$ with the true vacuum:

1. EWSB in SM: mass generation

- Rewrite: $\Phi(x) = \frac{1}{\sqrt{2}}\binom{\theta_2+i\theta_1}{v+H-i\theta_3} \simeq e^{i\theta_a(x)\tau^a(x)/v}\ \frac{1}{\sqrt{2}}\binom{0}{v+H(x)}$
- Gauge transf. (unitary gauge): $\Phi \to e^{-i\theta_a(x)\tau^a(x)}\Phi = \frac{1}{\sqrt{2}}\binom{0}{v+H(x)}$
- Develop covariant derivative: $|D_\mu\Phi|^2 = \left|\left(\partial_\mu - ig_2\frac{\tau_a}{2}W_\mu^a - i\frac{g_1}{2}B_\mu\right)\Phi\right|^2$
- Define: $W^\pm = \frac{W_\mu^1 \mp iW_\mu^2}{\sqrt{2}}$, $Z_\mu = \frac{g_2 W_\mu^3 - g_1 B_\mu}{\sqrt{g_2^2+g_1^2}}$, $A_\mu = \frac{g_2 W_\mu^3 + g_1 B_\mu}{\sqrt{g_2^2+g_1^2}}$
- And pick up terms bilinear in the fields $W^\pm, Z, A$ (i.e. $M_V^2 V_\mu^+ V^{-\mu}$)

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

$$M_W = \frac{1}{2}vg_2\ ,\ M_Z = \frac{1}{2}v\sqrt{g_2^2+g_1^2}\ ,\ M_A = 0\ ,$$

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 and thus $U(1)_{QED}$ 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):

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

$$\Phi \to \frac{1}{\sqrt{2}}\binom{0}{H+v} \Rightarrow m_e = \frac{f_e\, v}{\sqrt{2}},\ m_u = \frac{f_u\, v}{\sqrt{2}},\ m_d = \frac{f_d\, v}{\sqrt{2}}$$

1. EWSB in SM: the Higgs boson

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?

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 $V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$:

with $\Phi \rightarrow \frac{1}{\sqrt{2}}\binom{0}{H+v}$ the Lagrangian containing the H field becomes,

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

- **The Higgs boson mass is given by: $M_H^2 = 2\lambda v^2 = -2\mu^2$.**
- **The self–couplings are: $g_{H^3} = 3i\, M_H^2/v\,,\ g_{H^4} = 3iM_H^2/v^2$**
- **Higgs couplings to gauge bosons and fermions almost derived:**

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

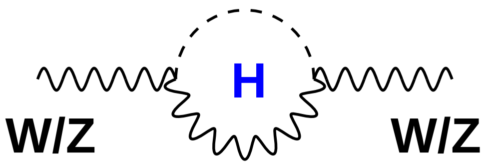
$$\Rightarrow g_{Hff} = im_f/v\,,\ g_{HVV} = -2iM_V^2/v\,,\ g_{HHVV} = -2iM_V^2/v^2$$

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

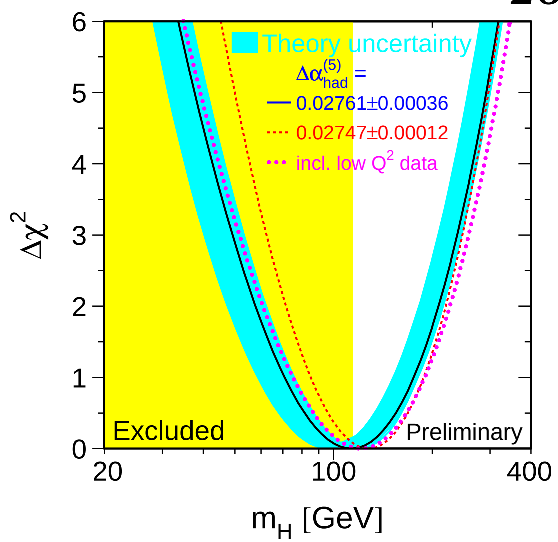
2. Constraints on $\mathrm{M_H}$

Indirect Higgs searches:

H contributes to RC to W/Z masses:



Fit the EW precision data:
one obtains $\mathrm{M_H} = 92^{+34}_{-26}$ GeV, or

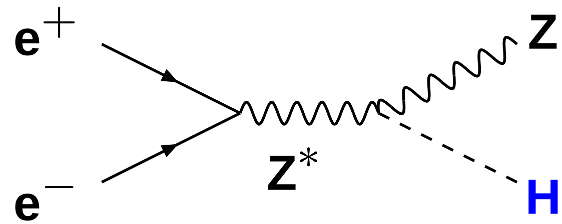


$\mathrm{M_H} \lesssim 161$ GeV at 95% CL

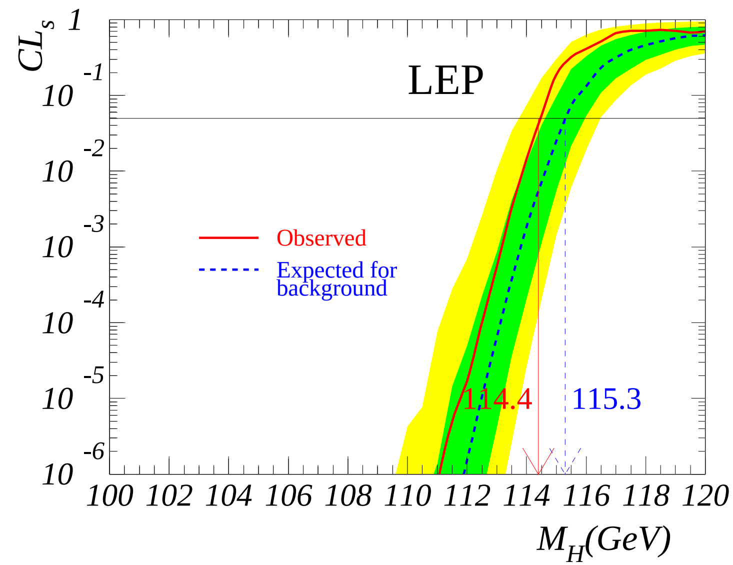
Beware: which $\mathrm{m_t}$ value?
also: slightly $\neq$ from Gfitter.

Direct searches at colliders:

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



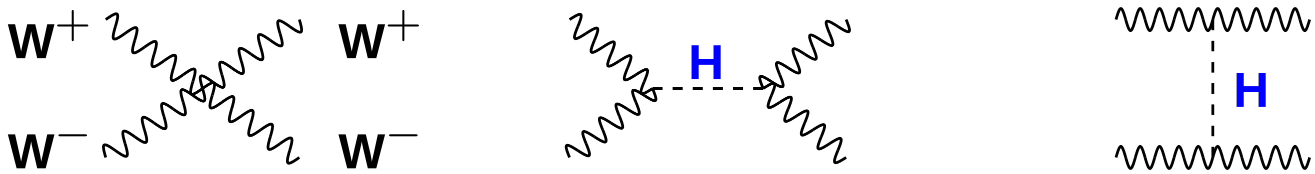
$\mathrm{M_H} > 114.4$ GeV @95%CL



Tevatron: $\mathrm{M_H} \neq 155-175$ GeV
LHC: $\mathrm{M_H} \neq 150-500$ GeV (appro
(to be discussed by Prof. Murray?)

2. Constraints on $\mathrm{M_H}$ perturbative unitarity

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



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

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

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

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

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

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

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

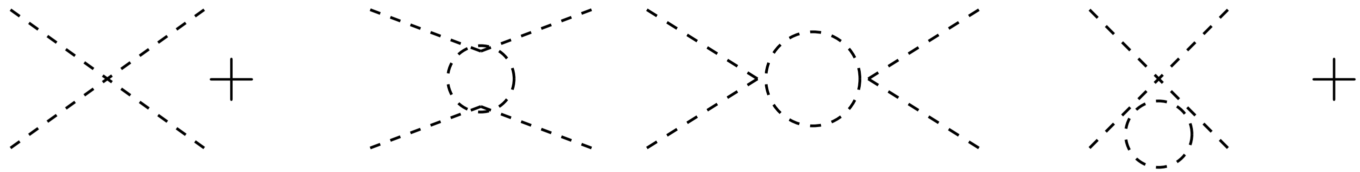
- For a very heavy or no Higgs boson, we have: $\mathrm{a_0} \xrightarrow{\mathrm{s} \ll \mathrm{M_H^2}} -\frac{\mathrm{s}}{32\pi \mathrm{v^2}}$

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

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

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

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



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 said to be trivial (no int.).**
- If $Q^2 \gg v^2, \lambda(Q^2) \to \infty$: **Landau pole at $Q = v \exp\left(\frac{4\pi^2 v^2}{M_H^2}\right)$.**

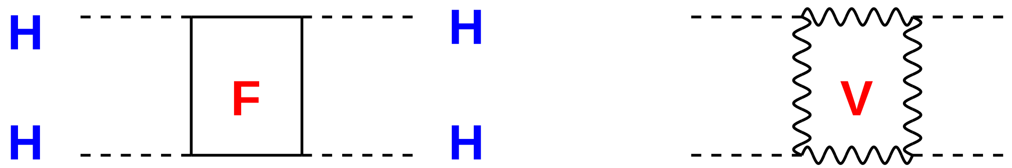
The SM is valid only at scales before λ becomes infinite:

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

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

2. Constraints on M_H: vacuum stability

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



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

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

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

v is not the minimum of the potentiel and the EW vacuum is instable.

$\Rightarrow$ Impose that the coupling λ stays always positive:

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

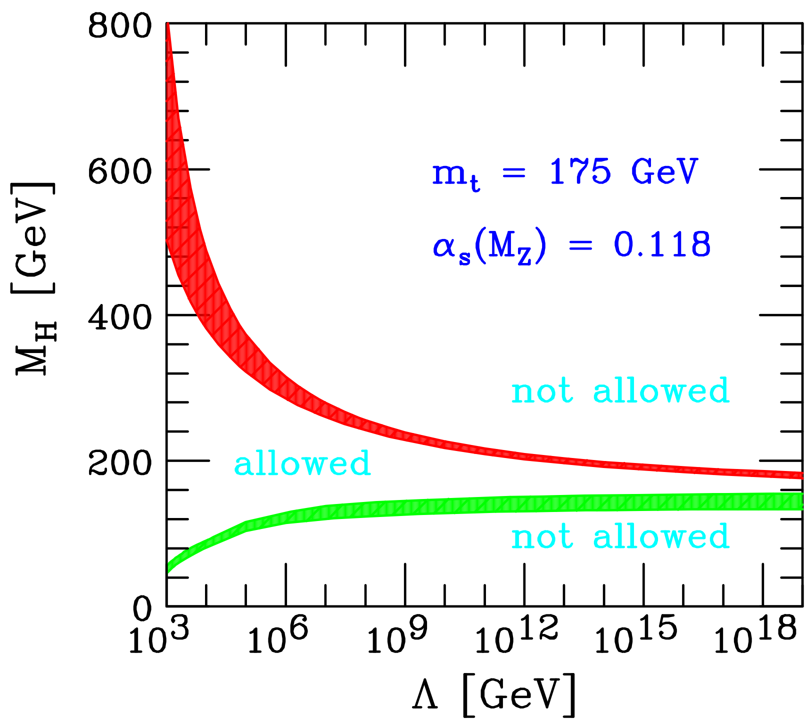
Very strong constraint: $Q = \Lambda_C \sim 1\ \mathrm{TeV} \Rightarrow M_H \gtrsim 70$ GeV

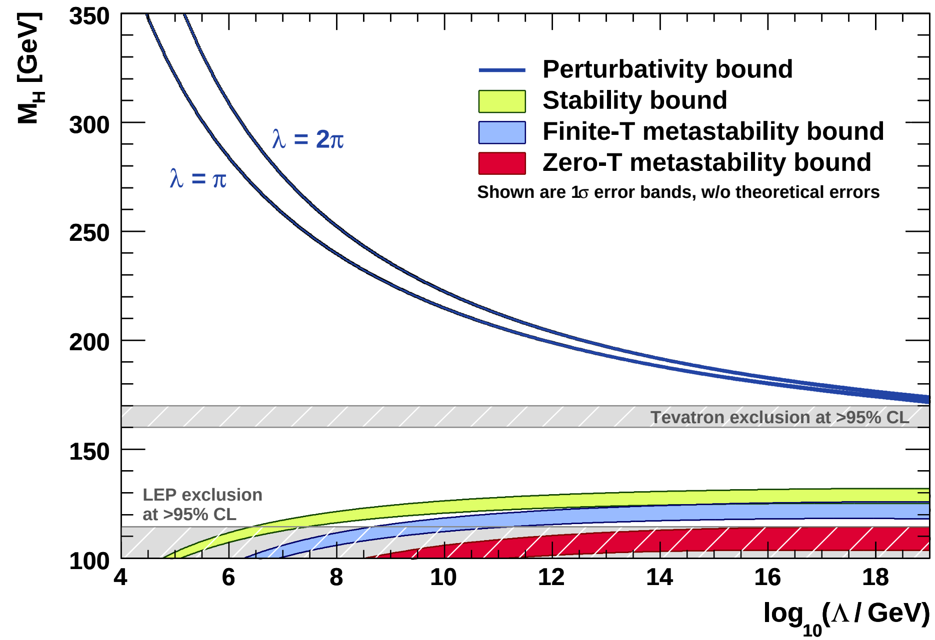
2. Constraints on M_H: triviality+stability

Combine the two constraints and include all possible effects:

– corrections at two loops; theoretical+exp. errors; refinements $\cdots$

– two ways to show triviality+stability constraint [a]





$$\Lambda_C \sim 10^3 \text{ GeV} \Rightarrow \quad 70 \text{ GeV} \lesssim M_H \lesssim 700 \text{ GeV}$$

$$\Lambda_C \sim 10^{16} \text{ GeV} \Rightarrow 130 \text{ GeV} \lesssim M_H \lesssim 180 \text{ GeV}$$

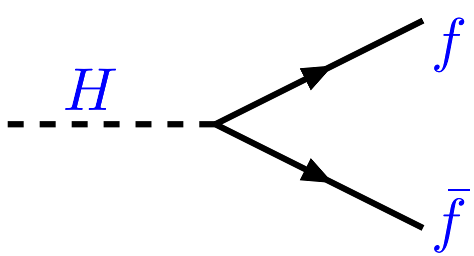
Cabibbo, Maiani, Parisi, Petronzio; Hambye, Riesselmann; J. Ellis et al.

3. Higgs decays

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

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

Higgs decays into fermions:



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

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

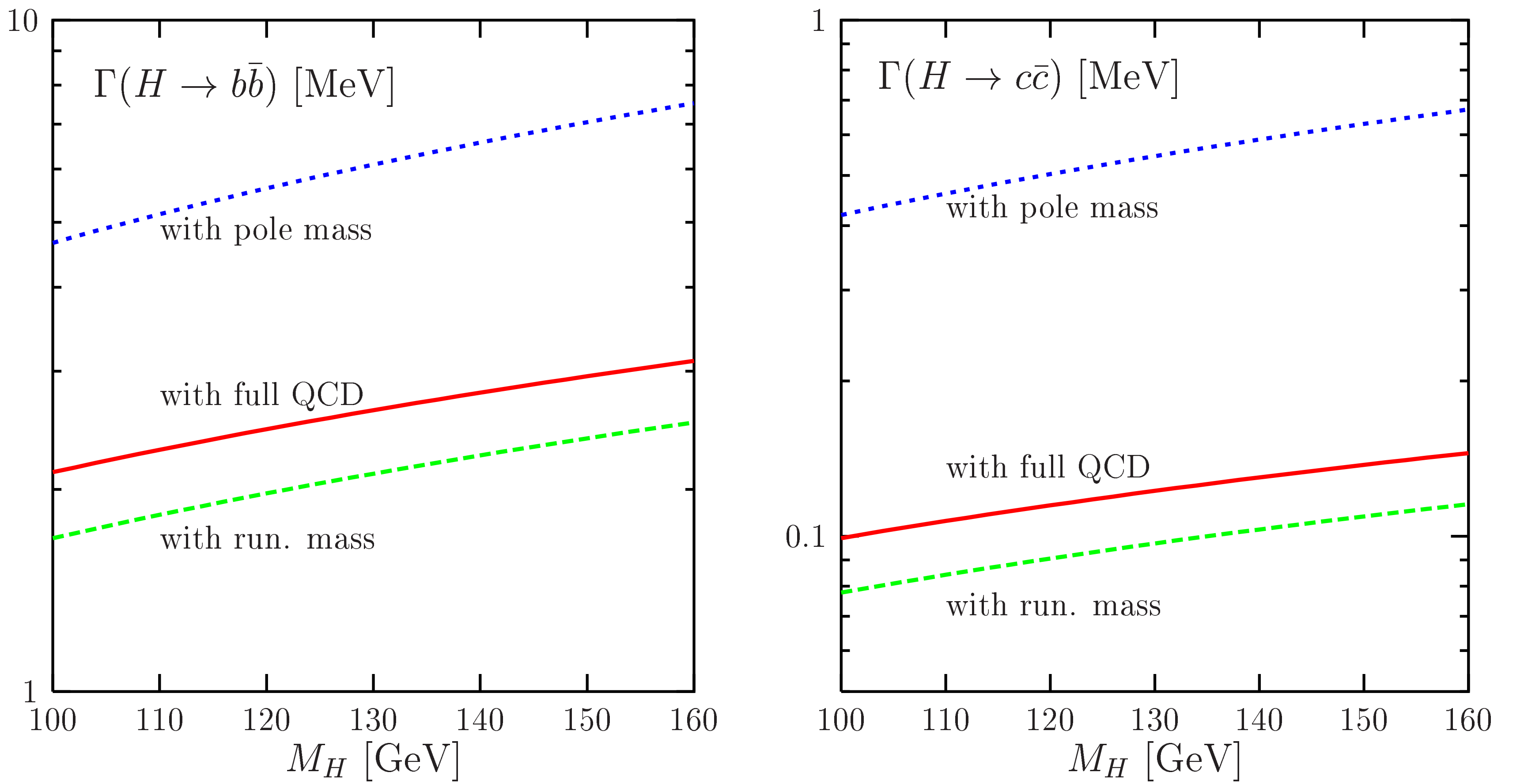
$$\mathrm{N_c} = \mathrm{color\ number}$$

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

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

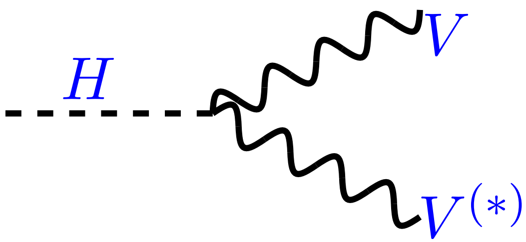
- Include also direct QCD corrections (3 loops) and EW (one-loop).

3. Higgs decays: QCD corrections



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

3. Higgs decays: decays into gauge bosons



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

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

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

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

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

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

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

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

- **For a light Higgs boson:**

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

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 $H \to b\bar{b}$

3. Higgs decays: decays into gauge bosons

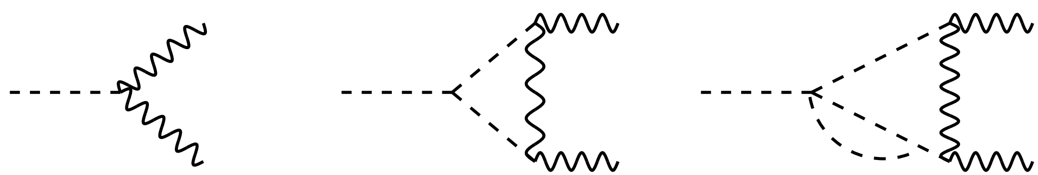
Electroweak radiative corrections to $\mathbf{H \to VV}$:

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

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

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

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



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

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

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

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

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

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

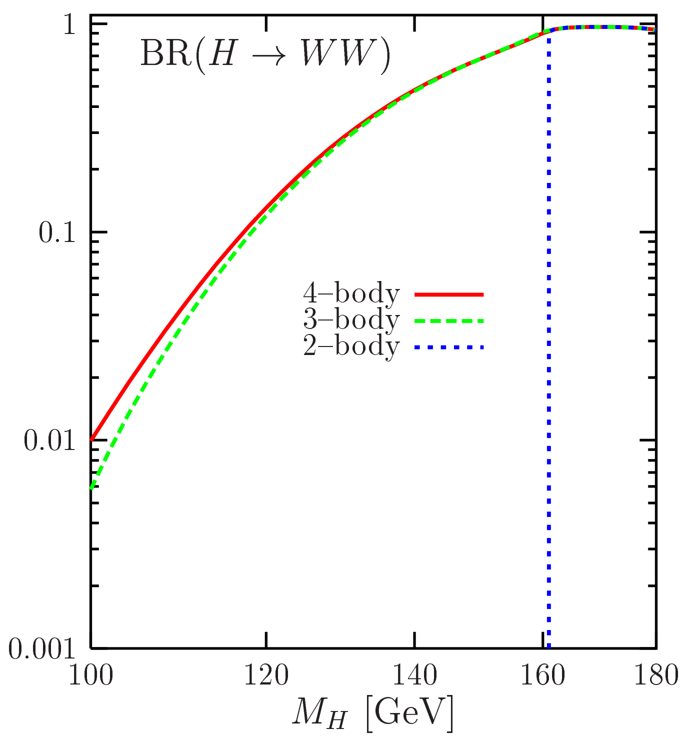
3. Higgs decays: decays into gauge bosons

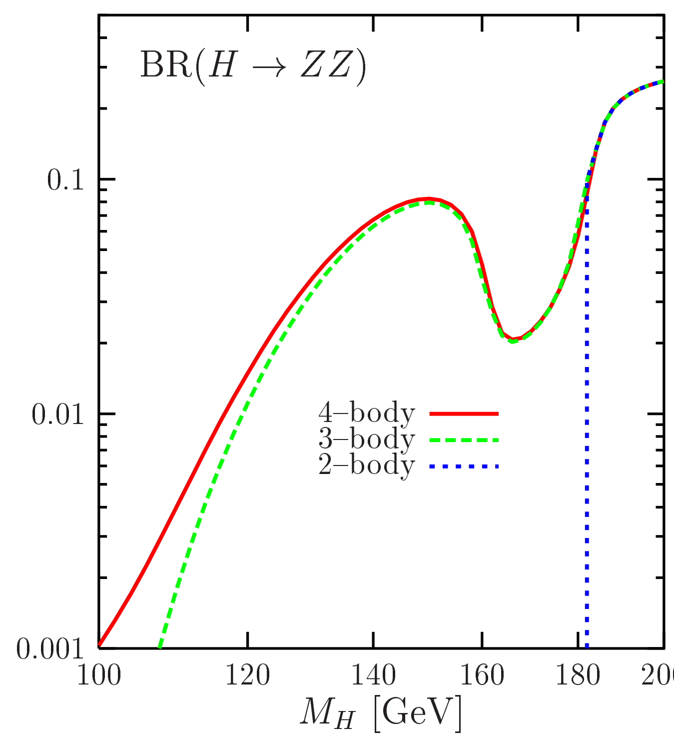
Combined 2+3+4 body decay calculation of $H \to V^* V^*$:

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

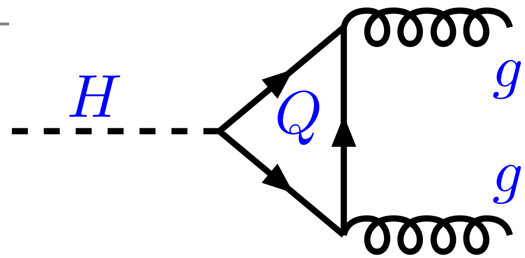
$\lambda(x, y; z) = (1 - x/z - y/z)^2 - 4xy/z^2$ **with** $\delta_{W/Z} = 2/1$ **and**

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





3. Higgs decays: decays into gluons



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

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

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

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

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

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

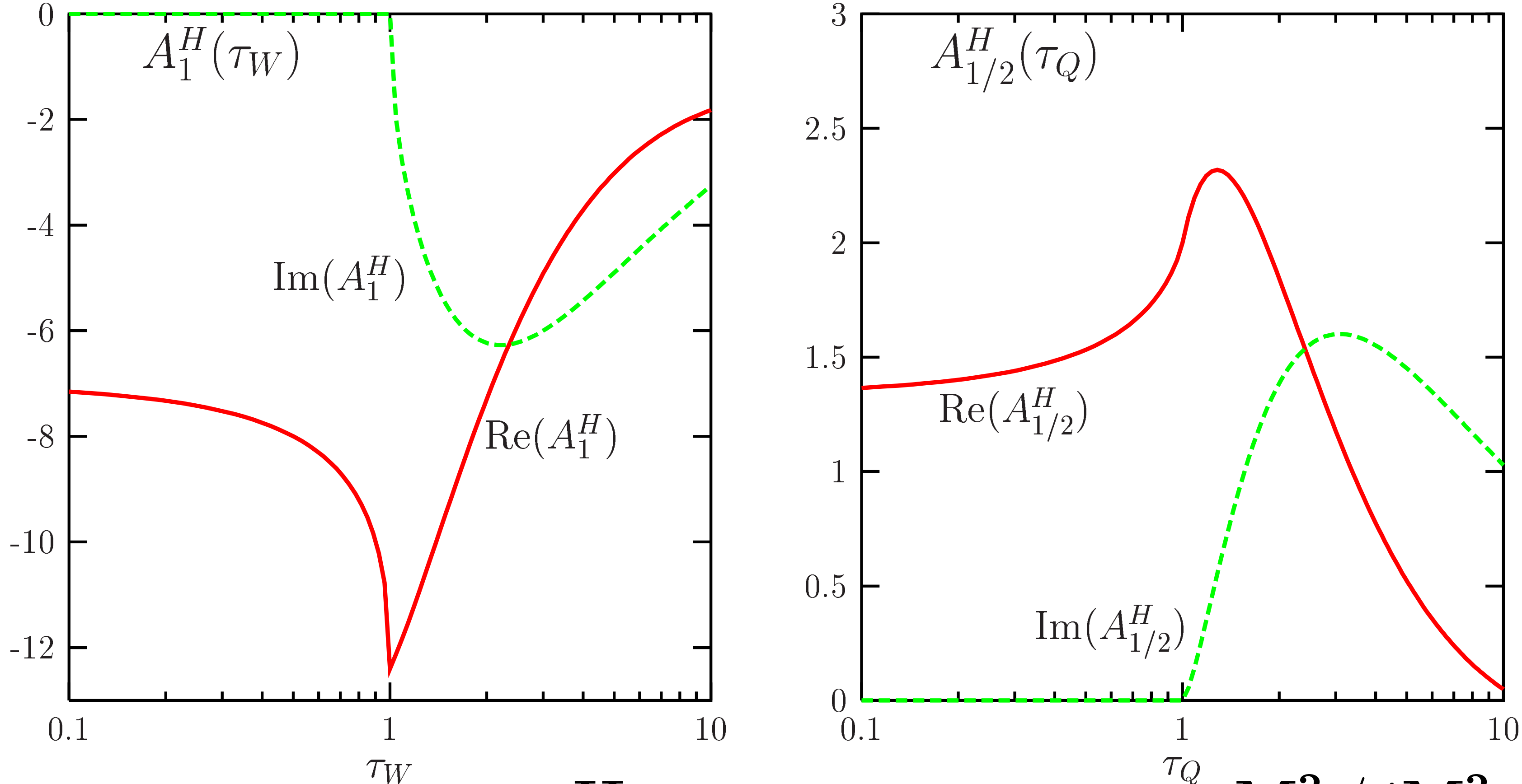
Good approximation in decay: include only t–loop with $m_Q \to \infty$. But:

- Very large QCD RC: 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!

3. Higgs decays: loop form factors

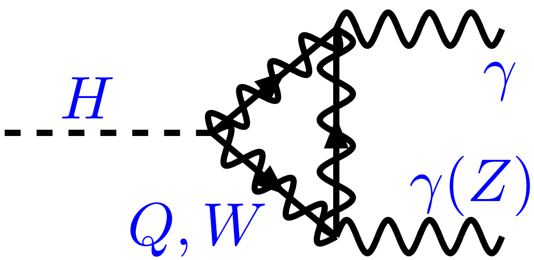


W and fermion amplitudes in $\mathrm{H} \to \gamma\gamma$ as function of $\tau_\mathbf{i} = \mathbf{M_H^2/4M_i^2}$.

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

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

3. Higgs decays: decays into photons



$$\Gamma = \frac{G_\mu \alpha^2 M_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c e_f^2 A_{\frac{1}{2}}^H(\tau_f) + A_1^H(\tau_W) \right|^2$$

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

$$A_1^H(\tau) = -[2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)]\,\tau^{-2}$$

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

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

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

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

3. Higgs decays: branching ratios

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

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

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

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

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

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

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

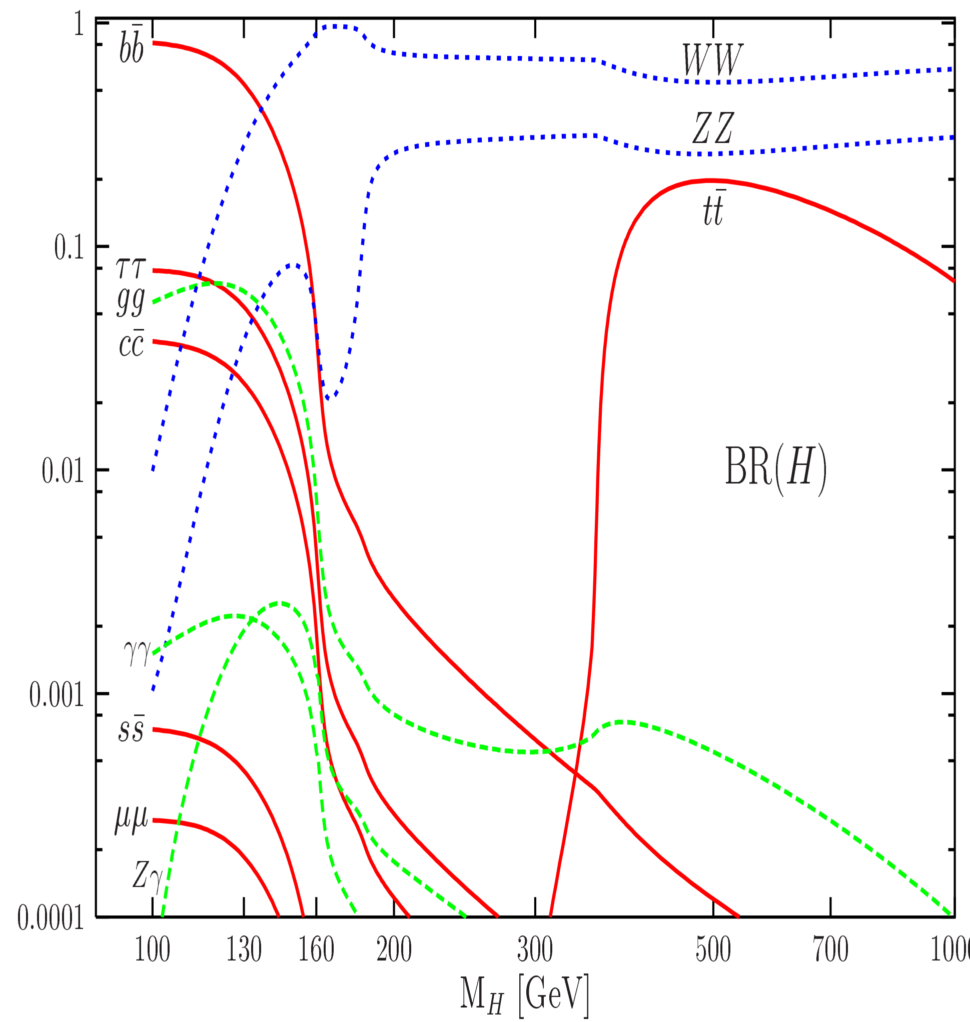
– $\mathrm{H \to WW, ZZ}$ **above (BR $\to \frac{2}{3}, \frac{1}{3}$)**

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

- **Total Higgs decay width:**

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

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



3. Higgs decays: total width

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

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

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

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

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

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

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

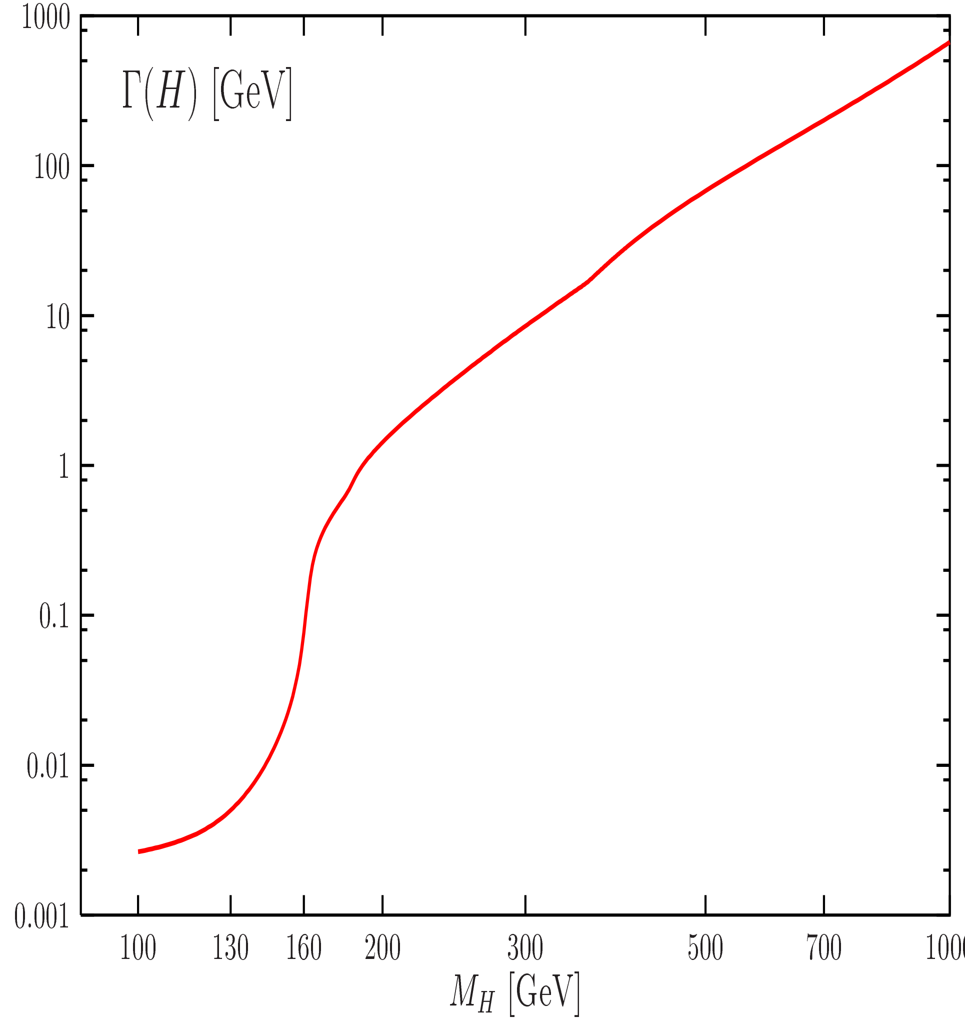
– $H \to WW, ZZ$ **above (BR $\to \frac{2}{3}, \frac{1}{3}$)**

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

- **Total Higgs decay width:**

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

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



3. Higgs decays: theory uncertainties

However: there are theoretical uncertainties....

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

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

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

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

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

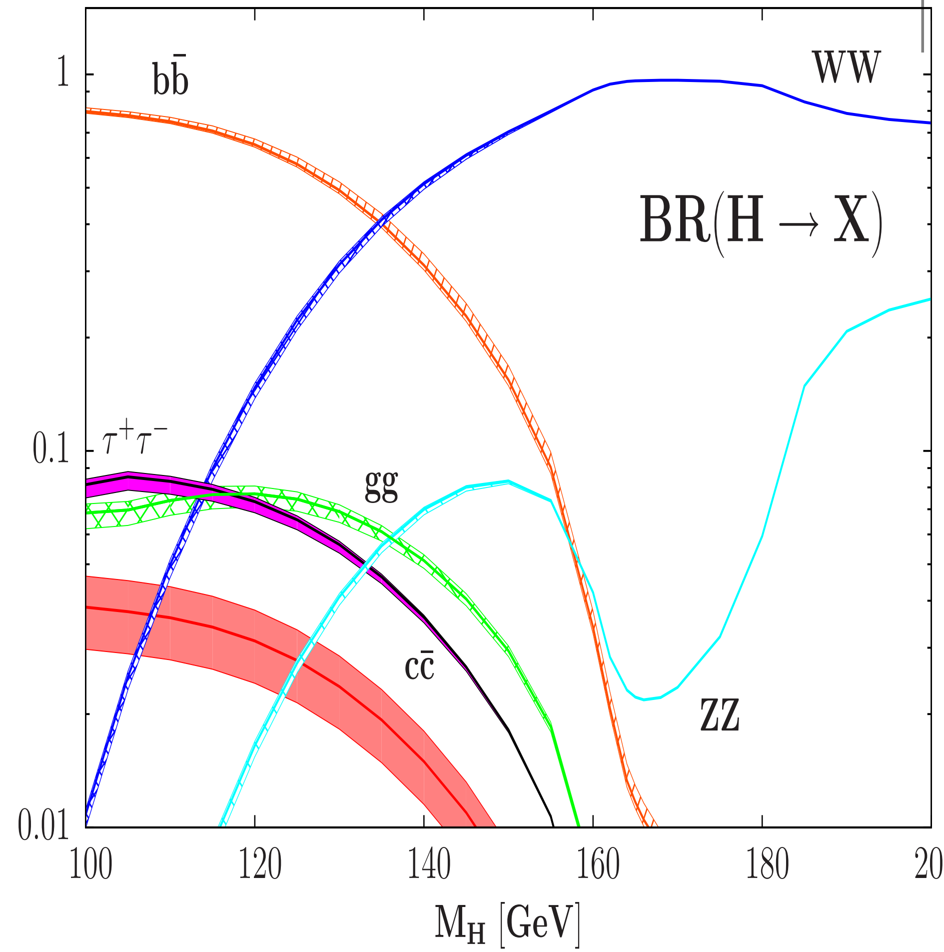
$\mathbf{\alpha_s(M_Z^2) = 0.1171 \pm 0.0014}$ **@NNLO**

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

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

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

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



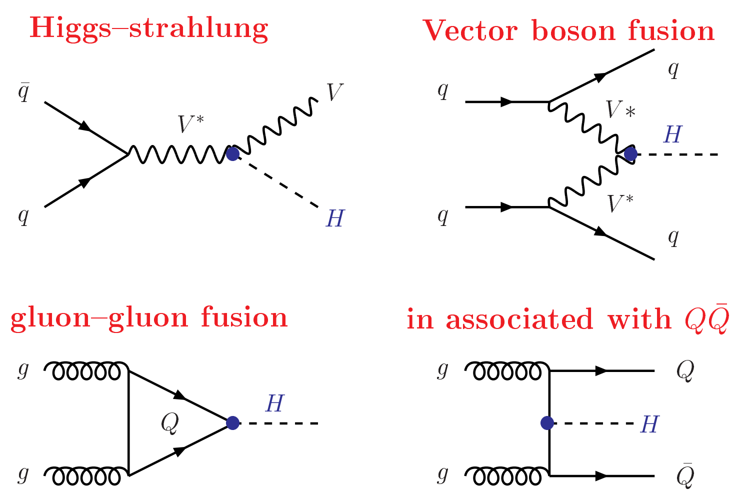
Baglio,AD

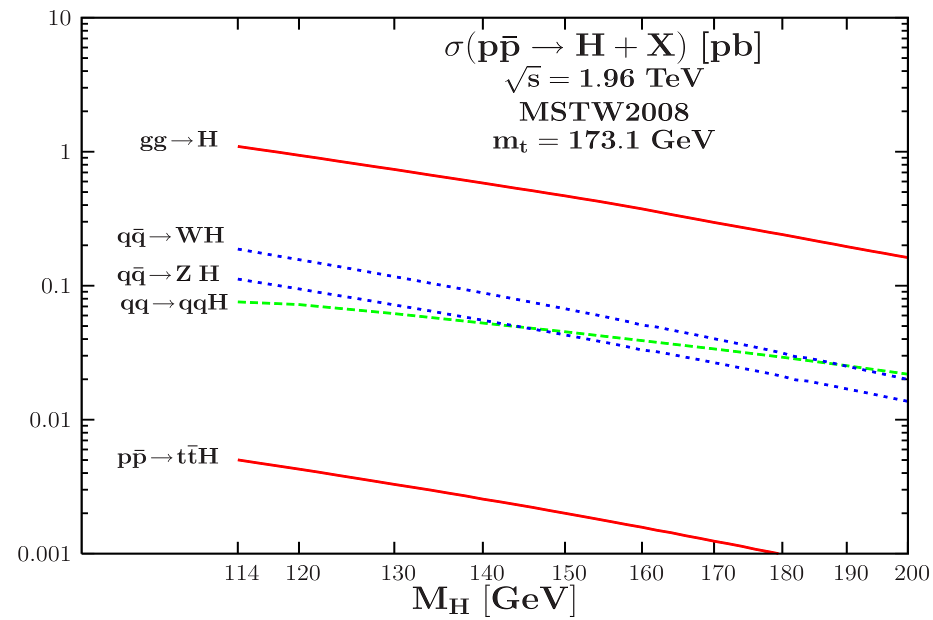
Include all items $\Rightarrow$ non-negligible uncertainties.

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

4. SM Higgs at hadron colliders: generalities

Main Higgs production channels





Large production cross sections

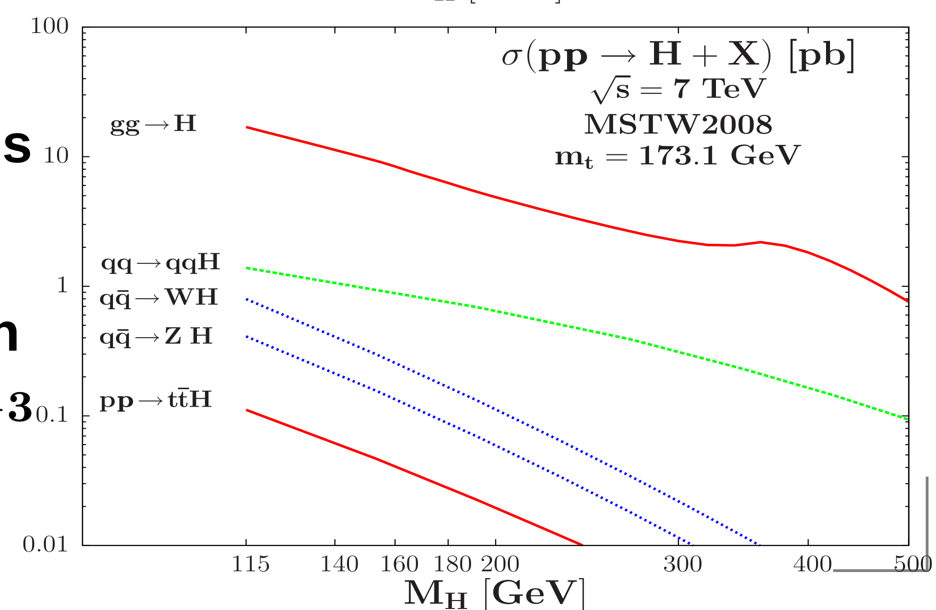
with gg$\longrightarrow$ H by far dominant process

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

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

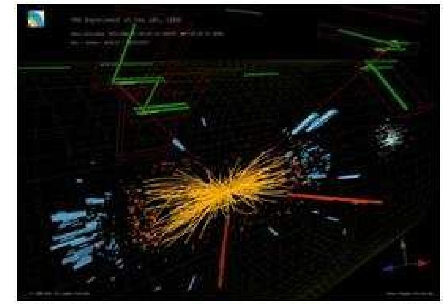
but eg BR(H$\to \gamma\gamma, \mathrm{ZZ} \to 4\ell) \approx 10^{-3}$

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



4. SM Higgs at hadron colliders: generalities

⇒ an extremely challenging task!



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

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

– trigger: get rid of uninteresting events...

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

– use specific kinematic features of Higgs

- Combine # decay/production channels

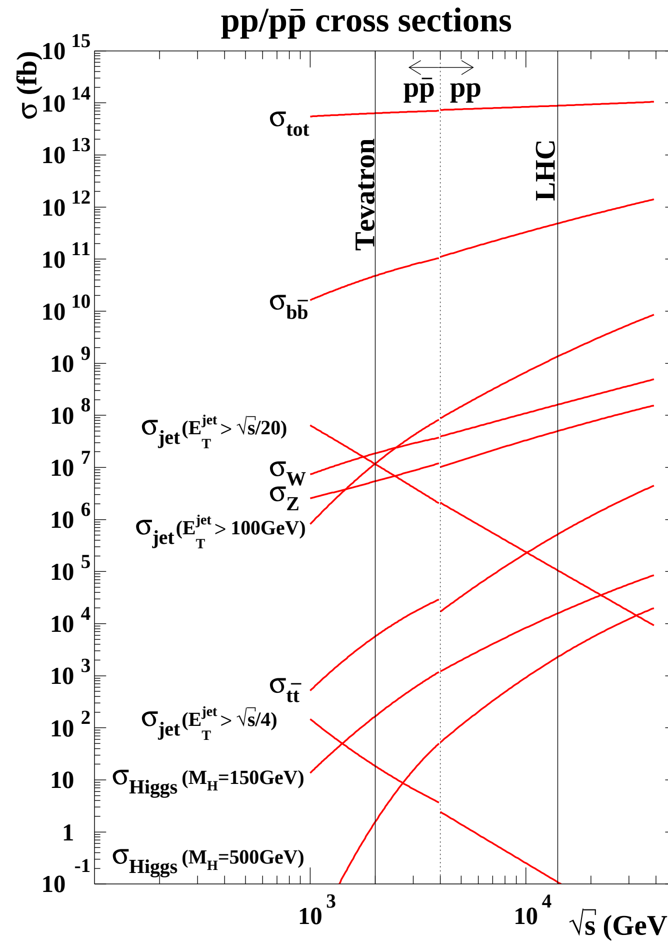
(and eventually several experiments...)

- Have a precise knowledge of S and B rates

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

- Gigantic experimental + theoretical efforts

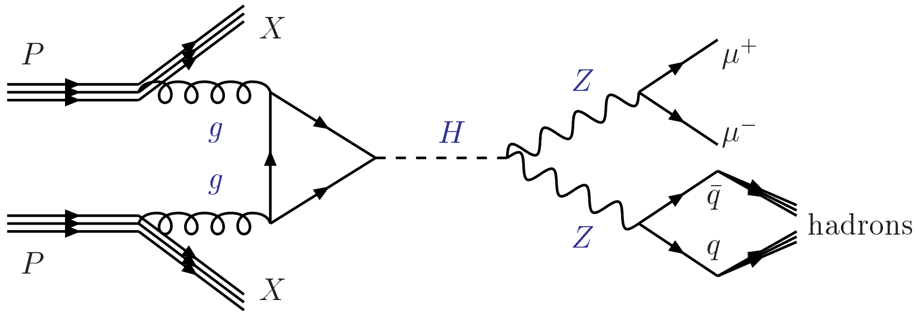
(more than 30 years of very hard work!)



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

4. SM Higgs at hadron colliders: generalities

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



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

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

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

Factorization theorem! Here discuss production/decay process.

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

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

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

Convolute with gluon densities to obtain total hadronic cross section

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

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

- **Since α_s is large, these corrections are in general very important.**
- **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. $\mathbf{p_T}, \eta, \frac{\mathbf{d}\sigma}{\mathbf{dM}}$) to distinguish S from B.

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

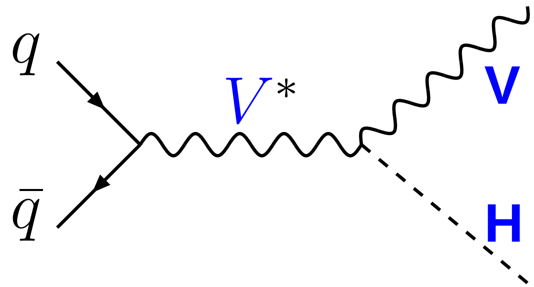
$\Rightarrow$ a lot of theoretical work is needed!

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

5. SM Higgs production: associated HV

Let us look at all the main Higgs production channels at the LHC:

The associated HV production:



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

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

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

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

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

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

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

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

5. SM Higgs production: associated HV

Radiative corrections needed:

– for precise determination of σ

– stability against scale variation

HO also needed to fix scales:

– renormalization μ_R for α_s

– factorization μ_F for matching.

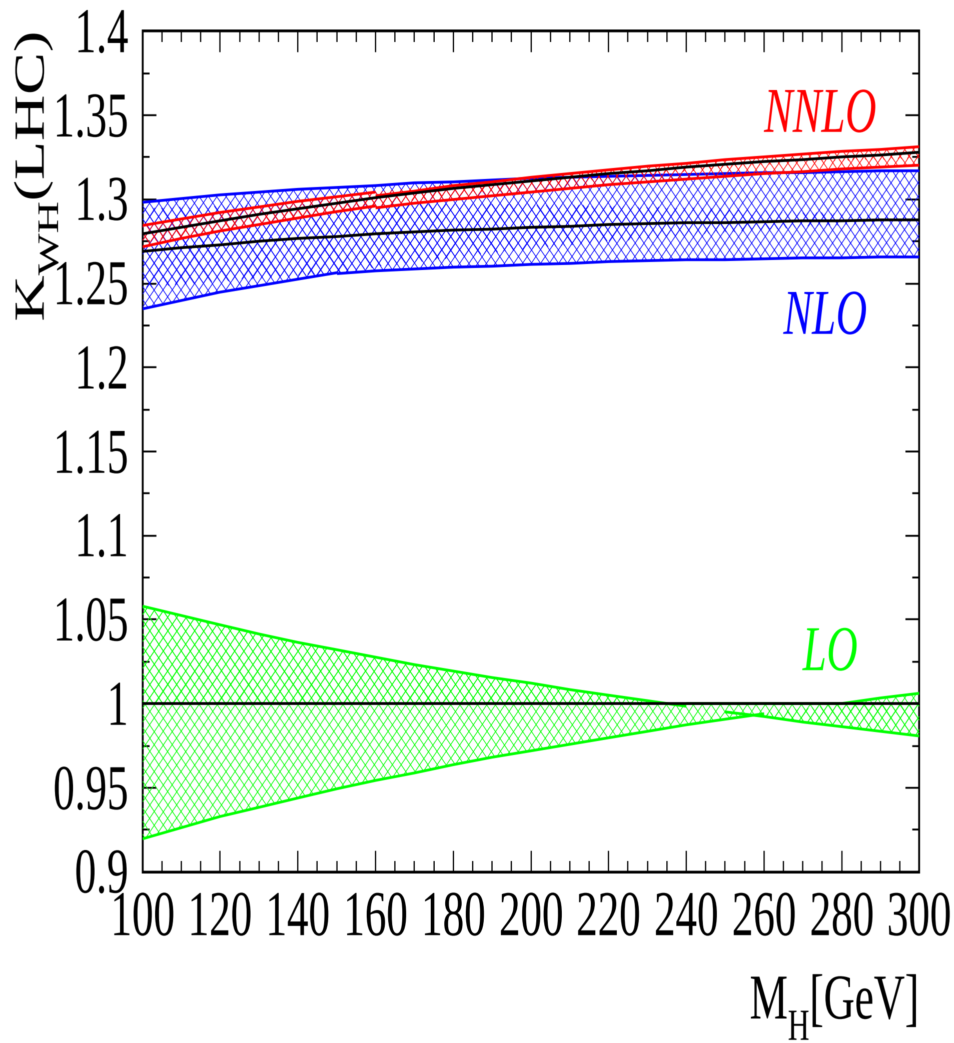
RC parameterized by K–factor:

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

Can also define K-factor at LO.

QCD RC known up to NNLO.

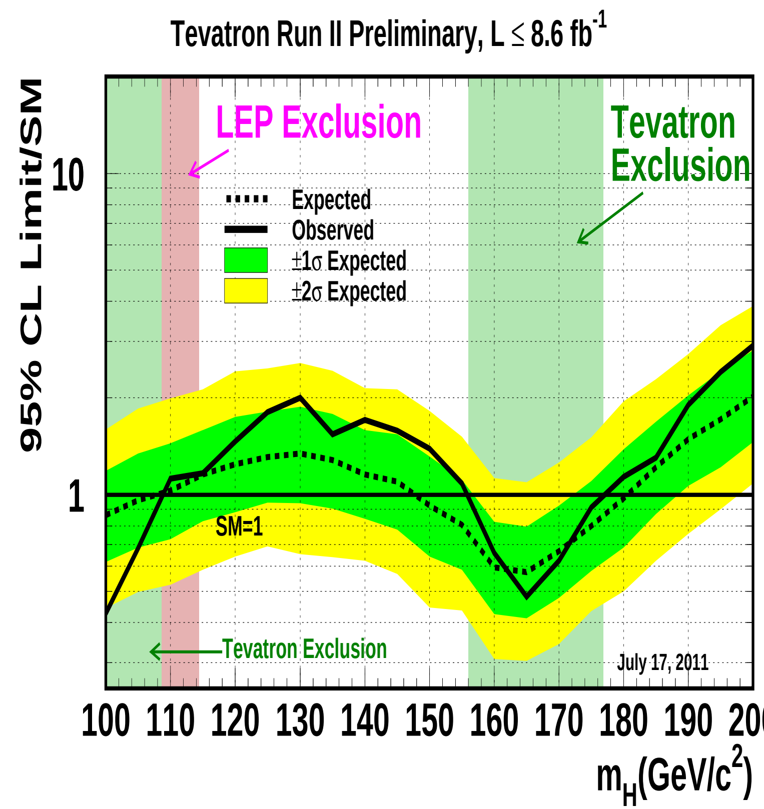
EW RC known at $\mathcal{O}(\alpha)$: small.



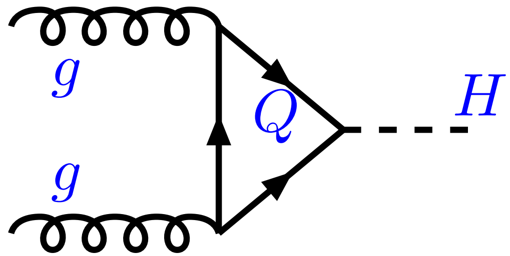
5. SM Higgs production: associated HV

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

However: WH channel is the most important at Tevatron:
$\mathrm{M_H} \lesssim 130$ **GeV:** $\mathrm{H} \to \mathrm{b\bar{b}}$
$\Rightarrow \ell\nu\mathrm{b\bar{b}},\ \nu\bar{\nu}\mathrm{b\bar{b}},\ \ell^+\ell^-\mathrm{b\bar{b}}$
(help for $\mathrm{HZ} \to \mathrm{b\bar{b}}\ell\ell, \mathrm{b\bar{b}}\nu\nu)$
$\mathrm{M_H} \gtrsim 130$ **GeV:** $\mathrm{H} \to \mathrm{WW}^*$
$\Rightarrow\ \ell^\pm\ell^\pm\mathrm{jj},\ 3\ell^\pm$
Sensitivity in the low H mass range excludes $\mathrm{M_H} = 100-110$ **GeV..**
range extended to $\mathrm{M_H} = 120$ **GeV?**



5. SM Higgs production: gg fusion



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

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

Related to the Higgs decay width into gluons discussed previously.

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

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

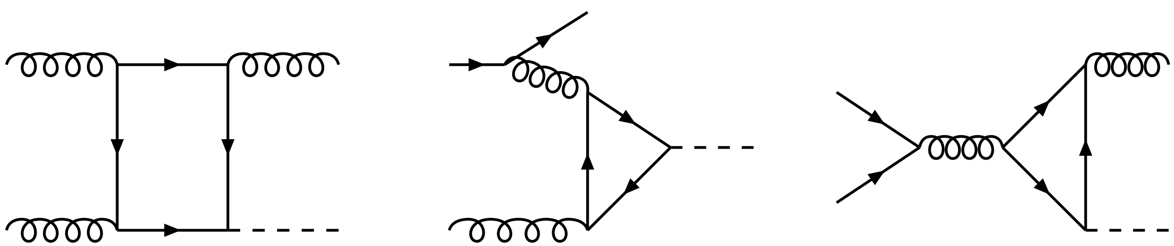
$gg \to H$ **is the leading production process at the LHC.**

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

5. SM Higgs production: gg fusion

QCD radiative corrections to $\mathrm{gg} \to \mathrm{H}$: NLO case

Typical diagrams for virtual and real QCD corrections to $gg \to H$ at NLO:



- **Regularization of UV divergences from virtual and IR+collinear divergences from real corrections in dimensional regularization.**
- **UV divergences cancelled by corresponding counterterms.**
- **IR divergences cancel in sum of virtual+real corrections.**
- **Collinear singularities are left: absorbed in PDF renormalization.**

5. SM Higgs production: gg fusion

- **Corrections known exactly, i.e. for finite $\mathbf{m_t}$ and $\mathbf{M_H}$, at NLO:**

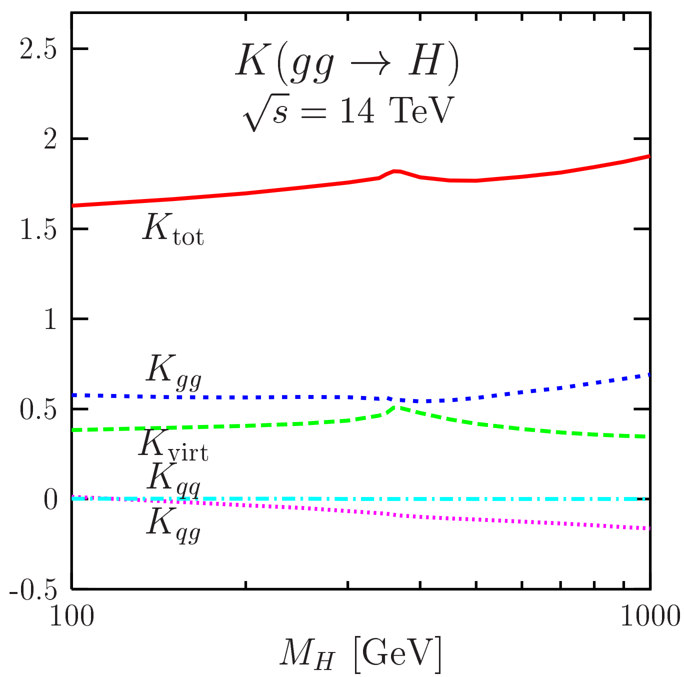
– quark mass effects are important for $\mathbf{M_H \gtrsim 2m_t}$.

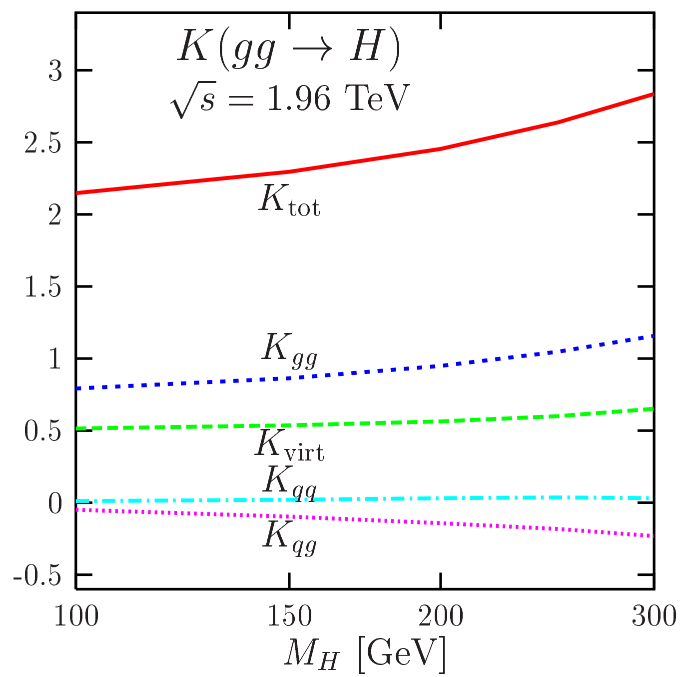
– $\mathbf{m_t \to \infty}$ is still a good approximation for masses below 300 GeV.

– corrections are large, increase cross section by a factor 1.6–1.9.

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

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





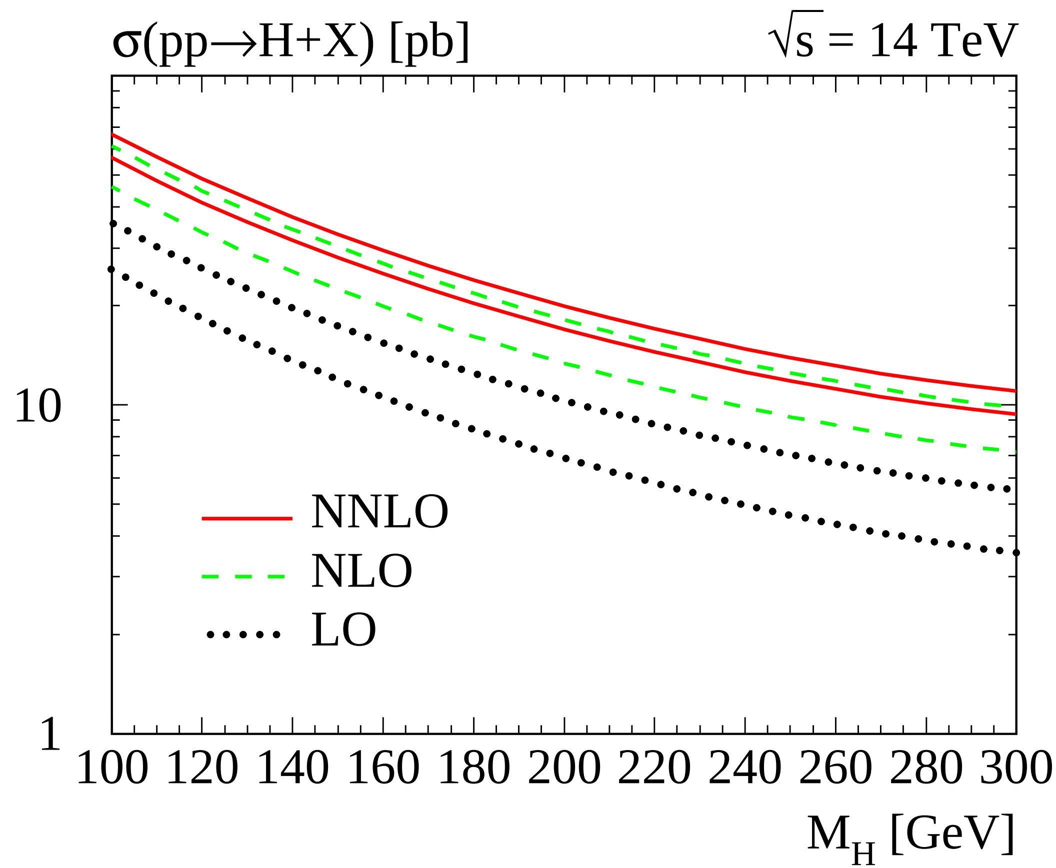
5. SM Higgs production: gg fusion

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

– moderate increase of cross section by 30% (good behavior of PT!).

– large stabilization with renormalization and factorization scales.

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

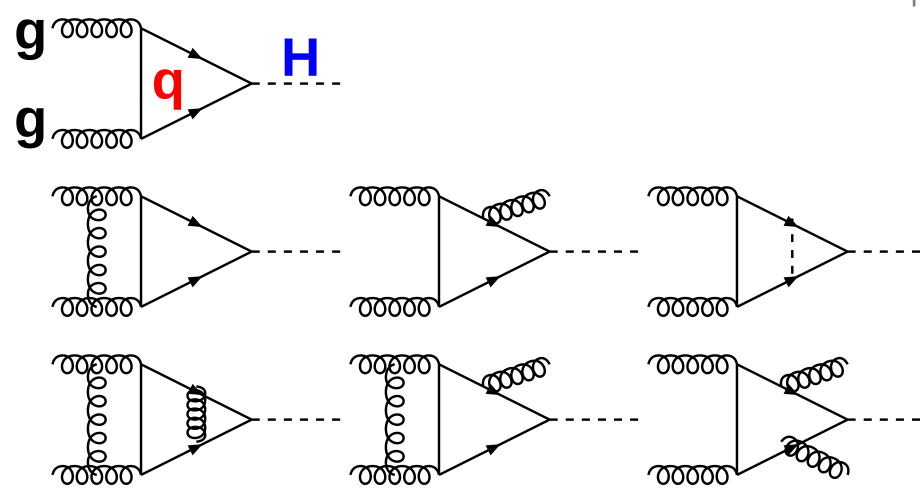


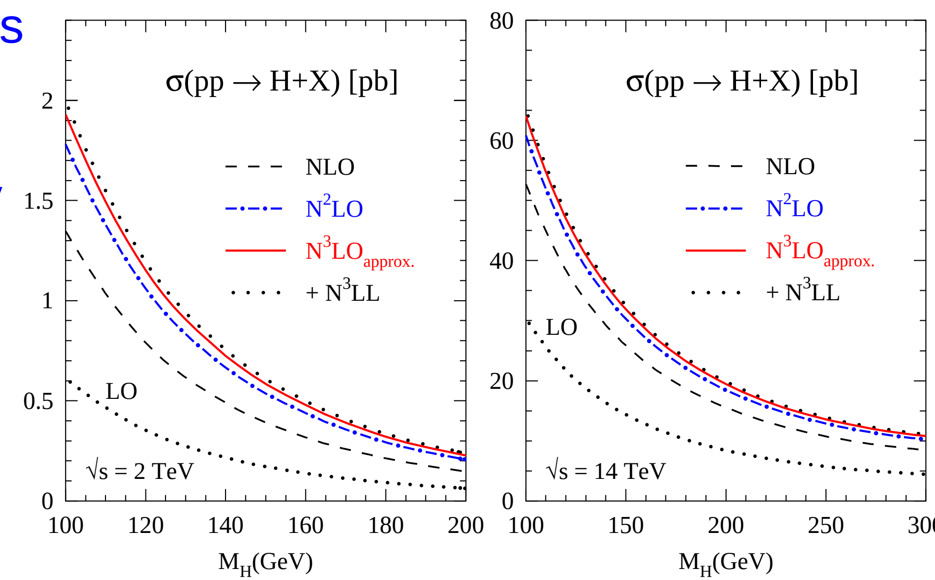
5. SM Higgs production: gg fusion summary

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

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

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





Moch+Vogt

5. SM Higgs production: gg fusion

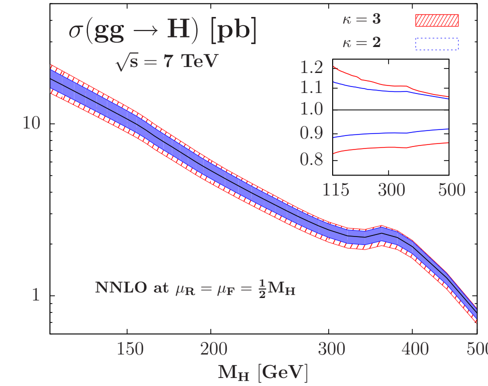
Despite of that, the $gg \to H$ cross section still affected by uncertainties

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

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

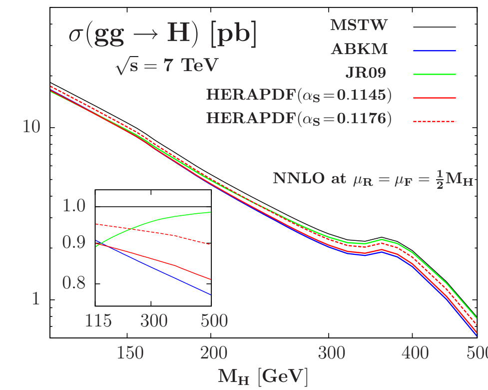
$$\mu_0/\kappa \le \mu_R, \mu_F \le \kappa\mu_0$$

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



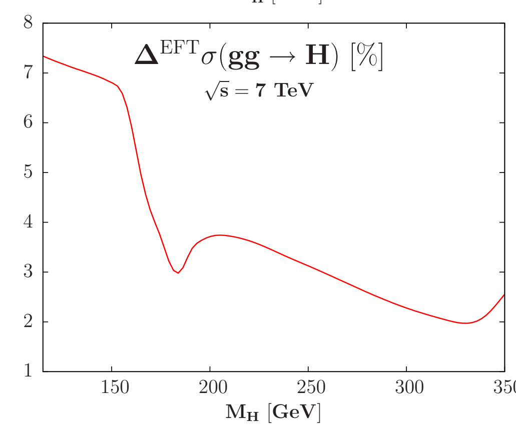
- **gluon PDF+associated α_s uncertainties:**

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



- **Uncertainty from EFT approach at NNLO**

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

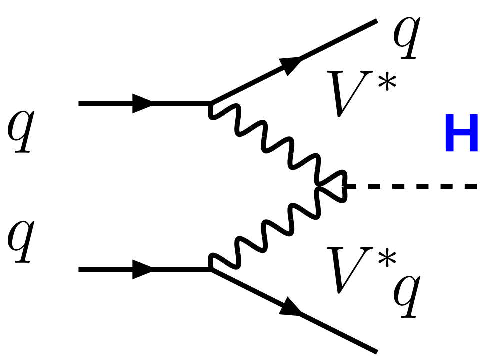


- **Include ΔBR(H$\longrightarrow$X) of at most few %**

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

LHC-HxsWG; Baglio+AD $\Rightarrow$

5. SM Higgs production: WW fusion



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

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

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

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

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).

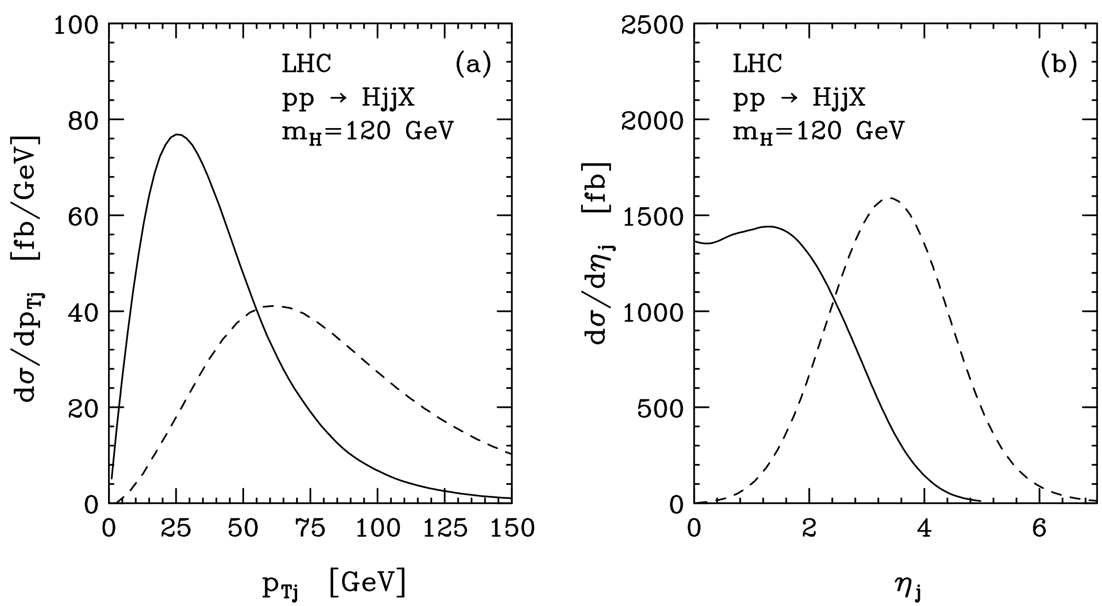
In fact: at LO in/out quarks are in color singlets and at NLO: no gluons are exchanged between first/second incoming (outgoing) quarks: QCD corrections only consist of known corrections to the PDFs!

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 P_T of $\mathcal{O}(\mathrm{M_V})$.**
- **Central jet vetoing: Higgs decay products are central and isotropic.**
- **Small hadronic activity in the central region no QCD (trigger uppon).**

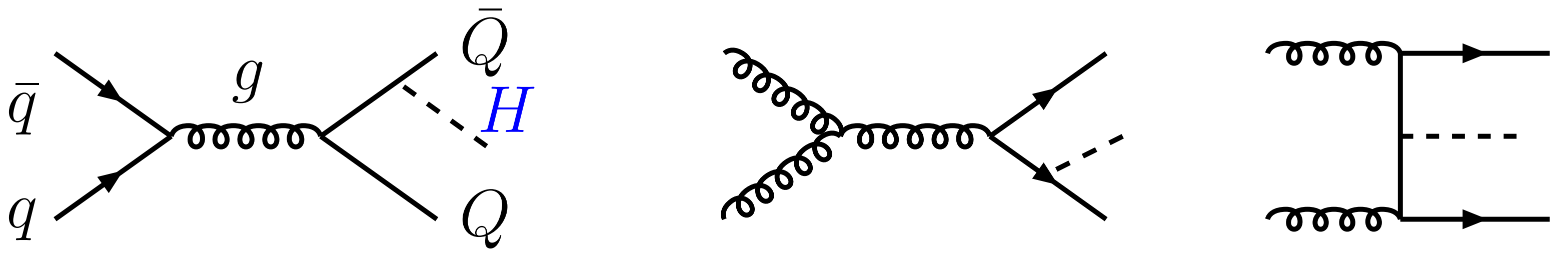
Allow to suppress the background to the level of H signal: $\mathrm{S/B} \sim 1$.



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

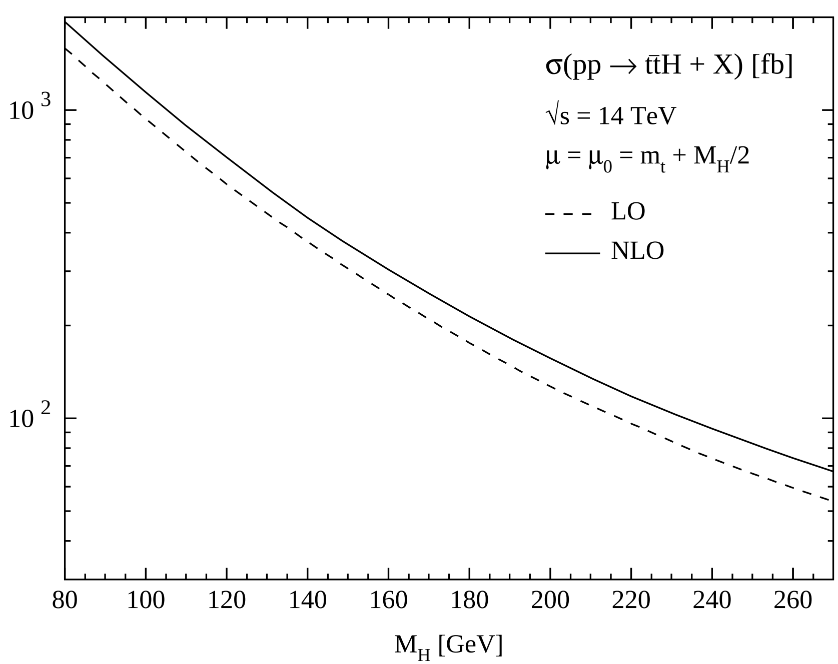
5. SM Higgs production: Htt production

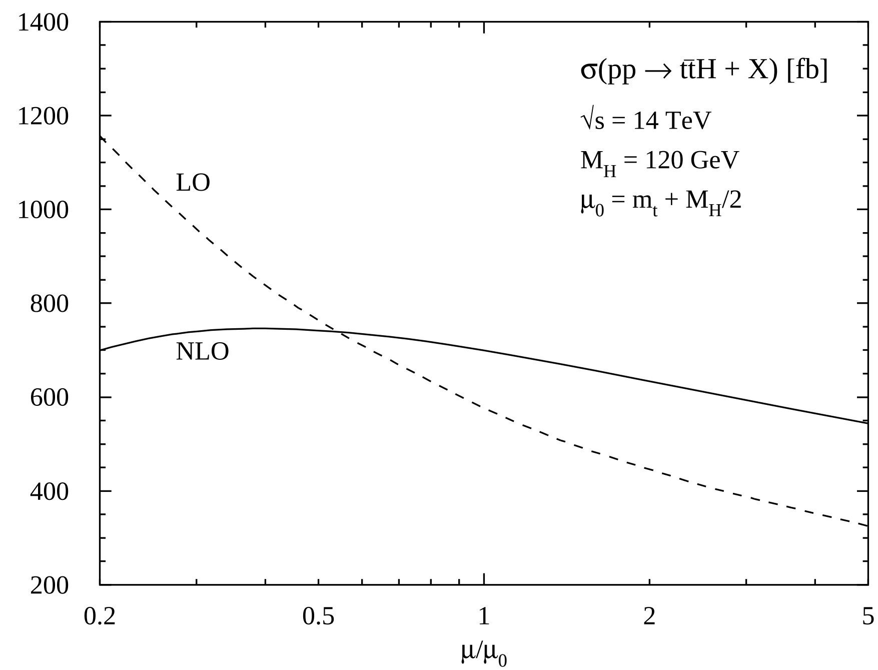
Most complicated process for Higgs production in pp: many channels:



NLO corrections calculateda fewyears ago (at last!):

small K–factors (~ 1.2) but strong reduction of scale variation!





5. SM Higgs production: Htt production

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

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

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

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

Interesting signals at the LHC for this process are:

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

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

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

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

But process very important for measurement of Htt Yukawa coupling!

5. SM Higgs production: summary

(better look at W. Murray slides...)

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

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

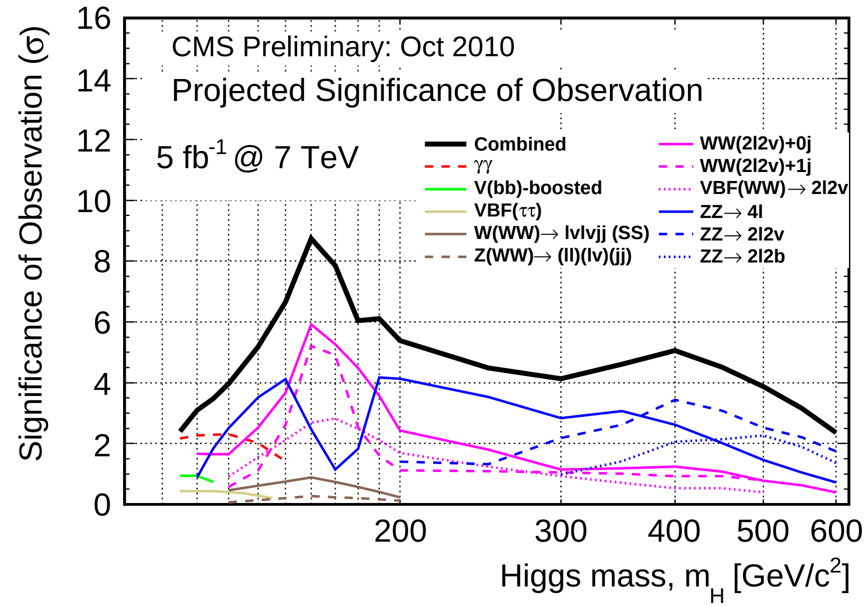
95%CL sensitivity for $\rm M_H \lesssim$600 GeV

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

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

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

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



Tevatron: some data still to be analyzed

now surpassed by lHC in all channels

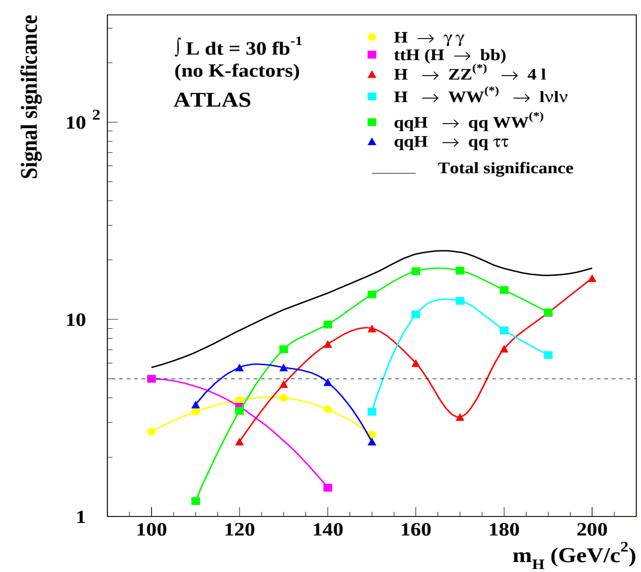
except $\rm HV \to b\bar{b}\ell X @ M_H\lesssim$130 GeV!

Full LHC: same as lHC plus some others

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

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

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



6. Measurement of Higgs properties

This/next year (?) we will find the Higgs (and maybe nothing else):

we celebrate, shake hands, drink champagne/ouzo, take care of our bets..

and should we declare Particle Physics closed and go home or fishing?

No! We need to check that it is indeed responsible of spontaneous EWSB!

Measure its fundamental properties in the most precise way:

- **its mass and total decay width,**
- **its spin–parity quantum numbers and chek $\mathrm{J^{PC} = 0^{++}}$,**
- **its couplings to fermions and gauge bosons and check that they are indeed proportional to the particle masses (fundamental prediction!),**
- **its self–couplings to reconstruct the potential $\mathrm{V_H}$ that makes EWSB.**

A very ambitious and challenging program!

which is even more difficult to achieve than the Higgs discovery itself...

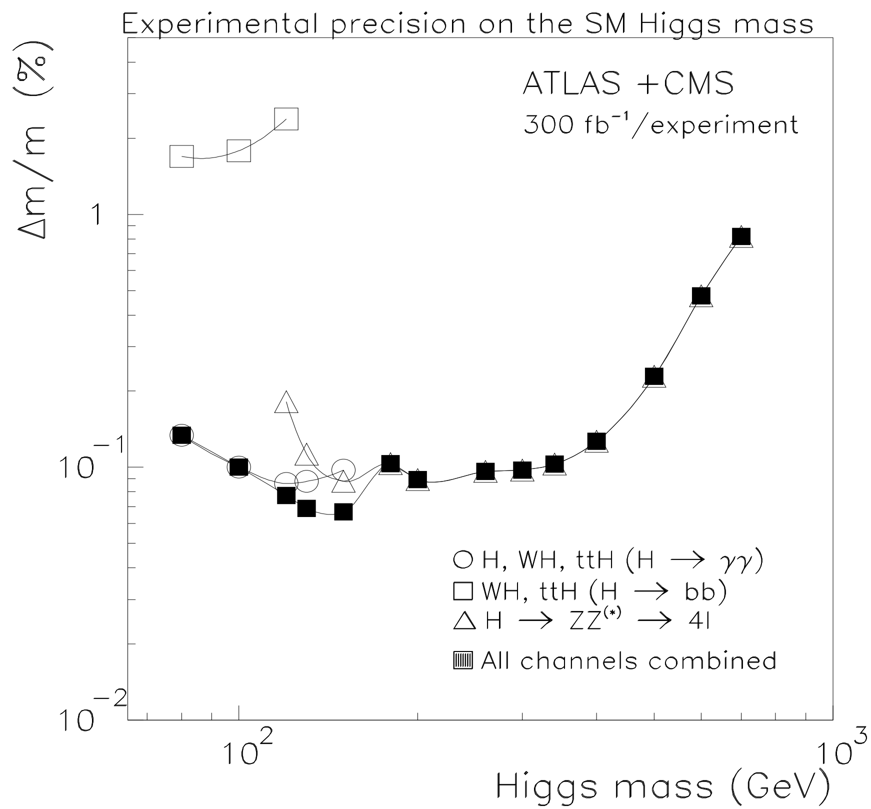
6. Higgs properties: mass and width

Higgs boson mass from:

– $\mathrm{H} \to \gamma\gamma$ for $\mathrm{M_H} \lesssim 130$ GeV

– $\mathrm{H} \to \mathrm{ZZ} \to 4\ell^{\pm}$ beyond

Final $\Delta\mathrm{M_H}/\mathrm{M_H} \sim 0.1\%$ to 1%.

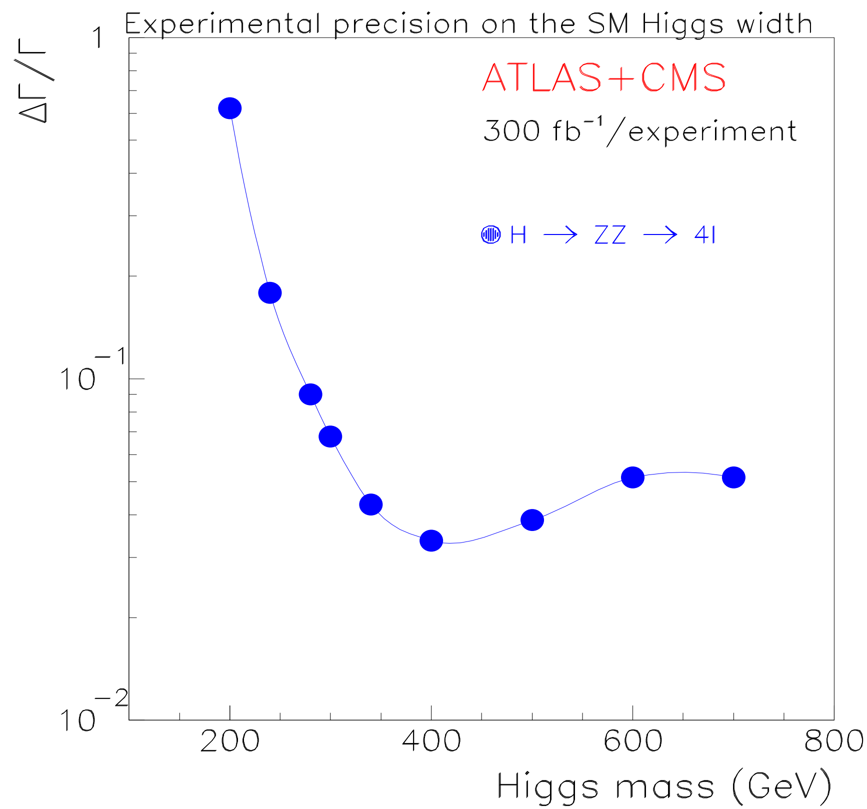


Higgs boson total width:

– Too small for $\mathrm{M_H} \lesssim 2\mathrm{M_Z}$

– $\mathrm{H} \to \mathrm{ZZ} \to 4\ell^{\pm}$ beyond

Final $\Delta\Gamma_\mathrm{H}/\Gamma_\mathrm{H} \sim$ a few %



However: for large $\mathrm{M_H}$ effects from large width are important!

6. Higgs properties: $\mathrm{J^{PC}}$ numbers

• Higgs spin:

$\mathrm{H \to \gamma\gamma}$: **rules out J=1 and fixes C=+.**

– not generalizable to $\mathrm{H \leftrightarrow gg (g \approx q)}$

– other possibility left, ex: J=2 (radion).

• Higgs parity:

– $\mathrm{H \to ZZ \to 4\ell^{\pm}}$ **rules out CP–odd.**

– spin–correlations in $\mathrm{gg \to H \to WW^{*}}$.

But need to check that H is pure CP–even

– challenging precision measurement,

– roughly doable in H→VV correlations.

Drawback: If H is mostly CP–even,

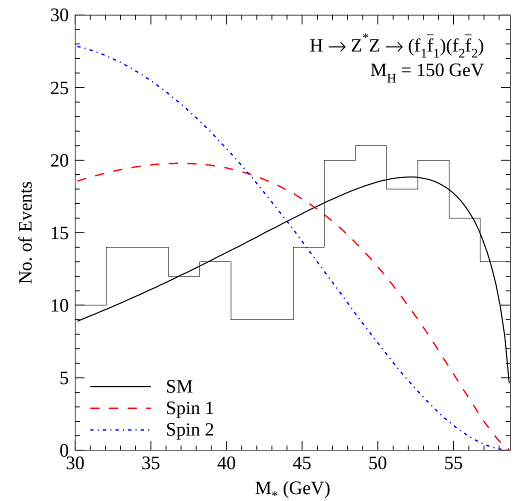
rates for $\mathrm{A \to VV}$ **are too small...**

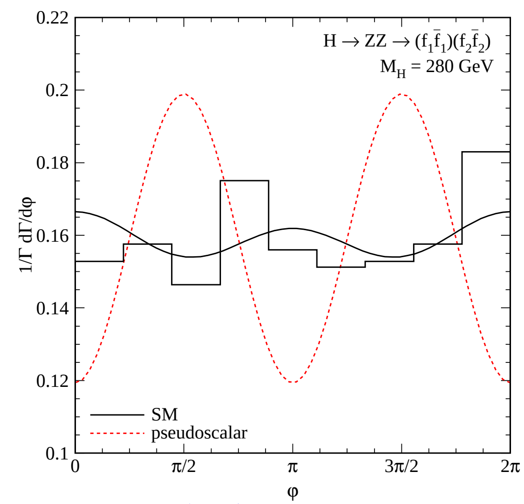
More convincing: look at Hff couplings

Possible but challenging channels:

$\mathrm{gg \to H \to \tau\tau}$ **or** $\mathrm{pp \to t\bar{t}H \to ttbb}$

$\mathrm{d\Gamma(H \to ZZ^{*})/dM_{*}}$ **threshold**





$\mathrm{d\Gamma(H \to ZZ)/d\phi}$ **azimuthal**

6. Higgs properties: Higgs couplings

• **Look at various H production/decay channels and measure $\mathrm{N_{ev}} = \sigma \times \mathrm{BR}$**

LHC with $\mathcal{L}=300$fb^{-1} (statistics only) $\Rightarrow$

• **Large errors mainly due to:**

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

– theory: PDFs, HO/scale, model dep...

• **For $\mathrm{M_H} \gtrsim 2\mathrm{M_Z}$ only $\mathrm{H}\to\mathrm{WW/ZZ}$ with $\sigma(\mathrm{gg}\to\mathrm{H})$ for indirect $\mathrm{g_{Htt}}$**

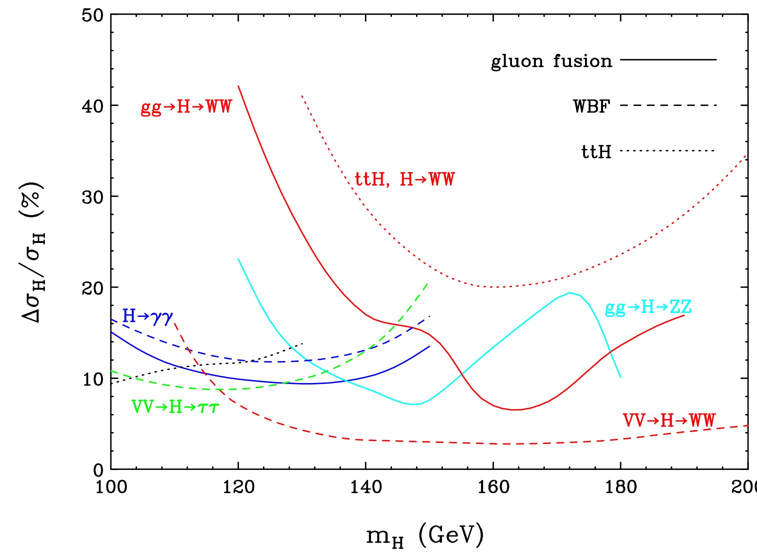
$\Rightarrow$ ratios of $\sigma \times \mathrm{BR}$: many errors drop out!

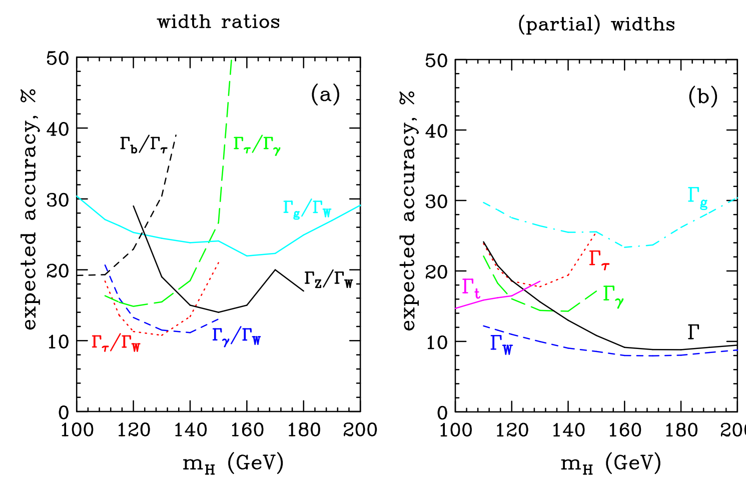
• **One obtains width ratios: $\Gamma_\mathrm{X}/\Gamma_\mathrm{Y}$**

• **Theory assumptions (no invisible, SU(2) invariance, some couplings are known,..)**

$\Rightarrow$ translate into $\Gamma_\mathrm{X} \propto \mathrm{g}^2_\mathrm{HXX}$ with precision: $\Delta \mathrm{g_{HXX}} = \frac{1}{2}\frac{(\Delta^{\mathrm{exp}}\Gamma + \Delta^{\mathrm{th}}\Gamma)}{\Gamma}$

$\Rightarrow$ reasonable precision of order 10–30%





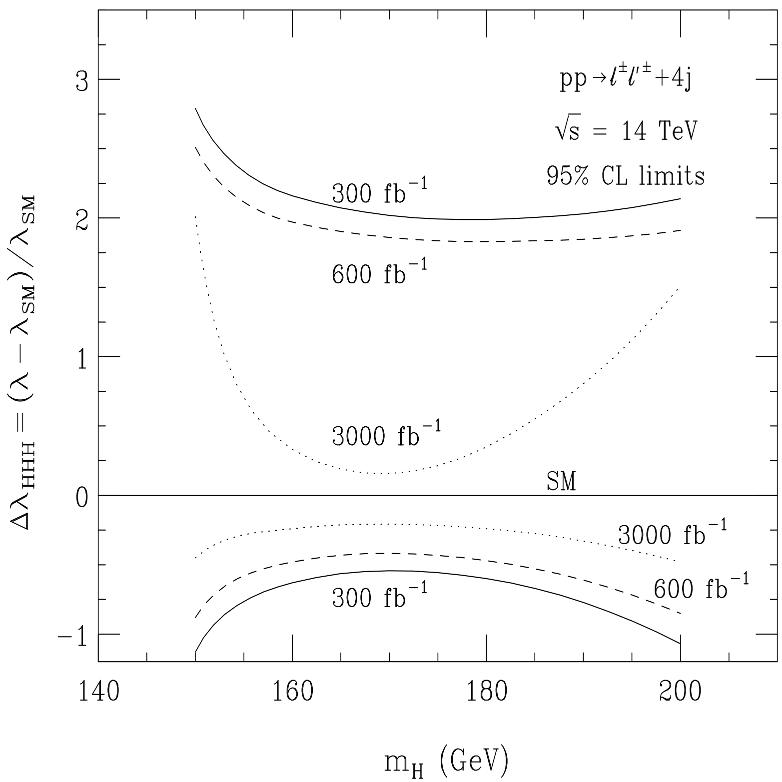
6. Higgs properties: Higgs self-couplings

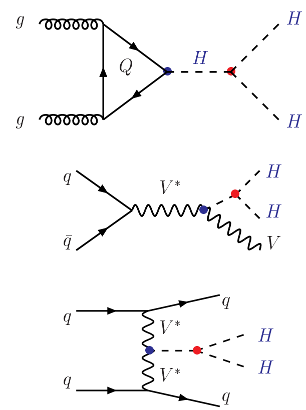
Important couplings to be measured: $g_{H^3}, g_{H^4} \Rightarrow$ access to V_H.

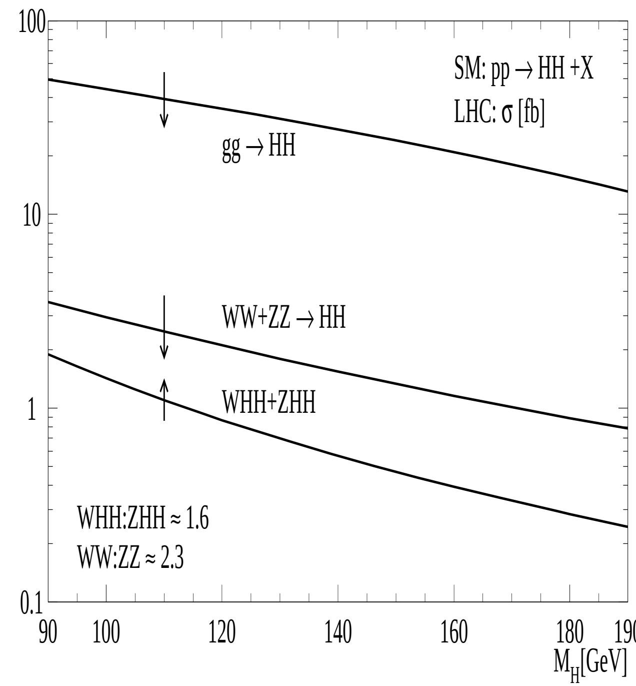
- g_{H^3} **from** $pp \to HH + X \;\Rightarrow$
- g_{H^4} **from pp⟶3H+X, hopeless.**

Relevant processes for HH prod:

only $gg \to HHX$ **relevant...**







- $H \to \gamma\gamma$ **decay too rare,**
- $H \to b\bar{b}$ **decay not clean**
- $H \to WW$ **at low M_H?**

– parton level analysis...

– look for $2\ell^{\pm}, 3\ell^{\pm} + \nu$+jets+

– needs very large luminosity.

7. The MSSM Higgs sector

Repitulation of Prof. Haber lectrure yesterday

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

- to cancel the chiral anomalies introduced by the new $\tilde{\rm h}$ field,
- give separately masses to d and u fermions in SUSY invariant way.

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

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

Only two free parameters at the tree level: $\tan\beta, \mathbf{M_A}$; others are:

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

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

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

We have important constraint on the MSSM Higgs boson masses:

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

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

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

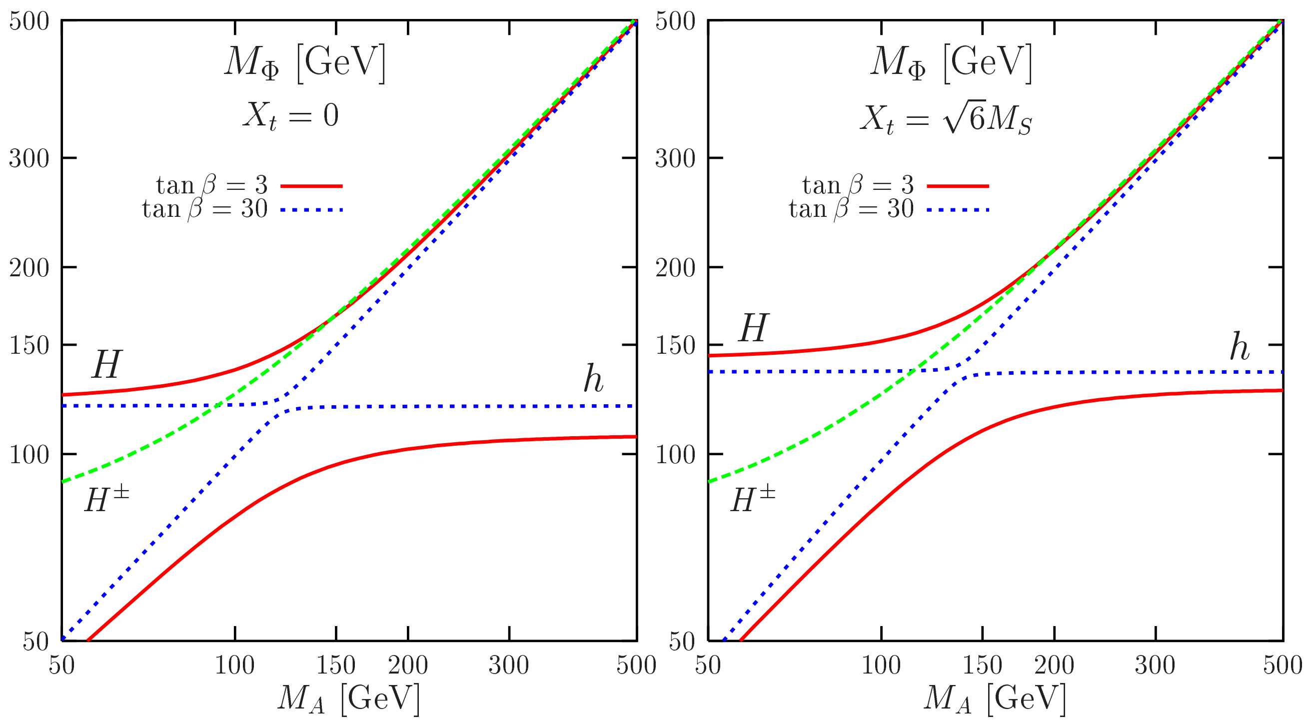
7. The MSSM Higgs sector: Higgs masses

Radiative corrections very important in the MSSM Higgs sector.

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

$$\mathbf{\Delta M_h^2 = \frac{3g^2}{2\pi^2}\frac{m_t^4}{M_W^2}\log\frac{m_{\tilde{t}}^2}{m_t^2}} \text{ large: } \xrightarrow{\mathbf{M_h^{max} \to M_Z + 40\,GeV}} \gtrsim \mathbf{115}\,\mathrm{GeV}$$

- **Full one–loop corrections + approximate two–loop important.**
- **After RC:** $\mathbf{M_h^{max} \approx 110 - 140\,GeV}$ **depending on** $\tan\beta$ **and** $\mathbf{A_t}$



7. The MSSM Higgs sector: Higgs couplings

Higgs decays and cross sections strongly depend on couplings.

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.**

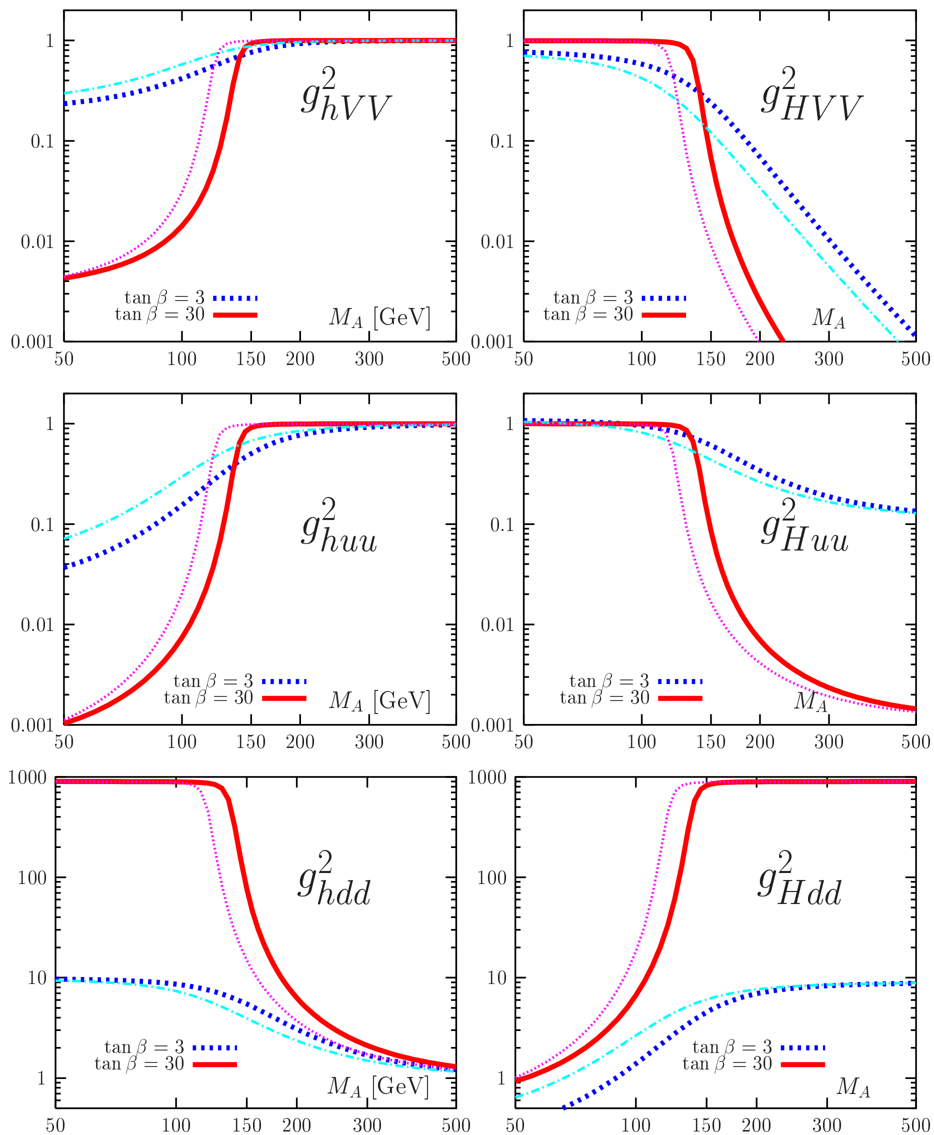
– **For $\tan\beta \gg 1$: couplings to b quarks ($\mathrm{m_b}\tan\beta$) very strong.**

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

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

7. The MSSM Higgs sector: SUSY Higgs couplings

Including radiative corrections just as in the case of the Higgs masses:



8. MSSM Higgs at the LHC: decays

Higgs decays in the MSSM:

General features:

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

(in particular in decoupling limit)

$\mathrm{h} \to \mathrm{b\bar{b}}$ and $\tau^+\tau^-$ same or enhanced

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

(no VV decays, hZ suppressed).

- **H: same as A in general**

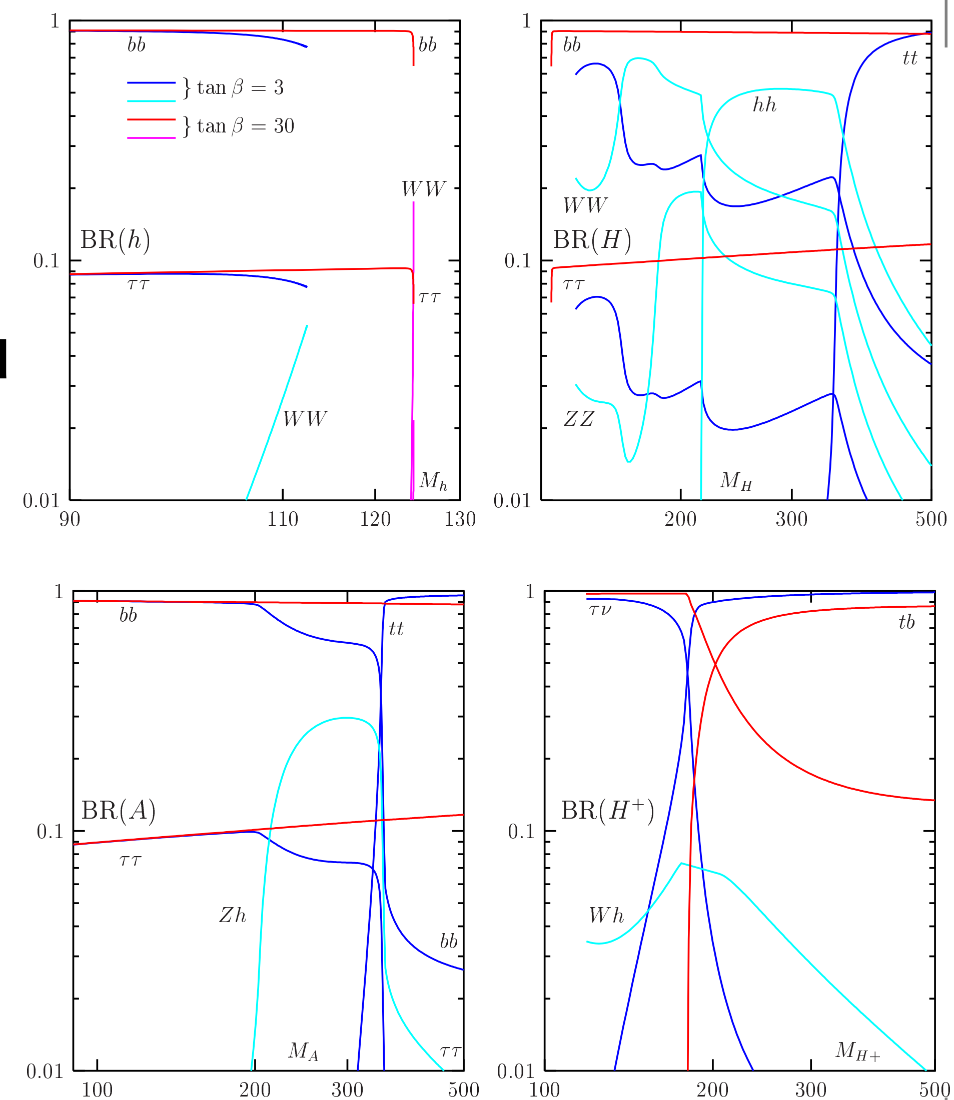
$(\mathrm{WW}, \mathrm{ZZ}, \mathrm{hh}$ decays suppressed).

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

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

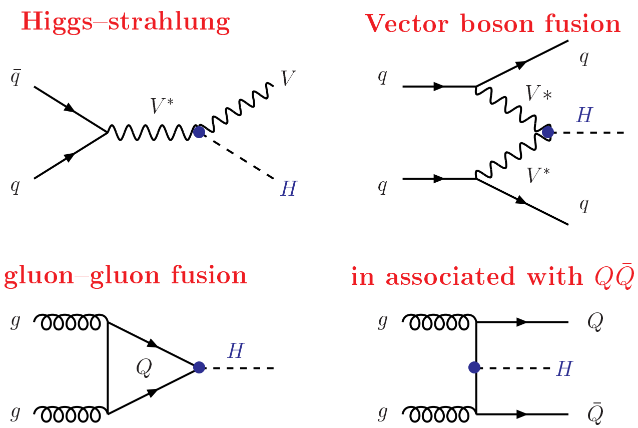
Possible new effects from SUSY

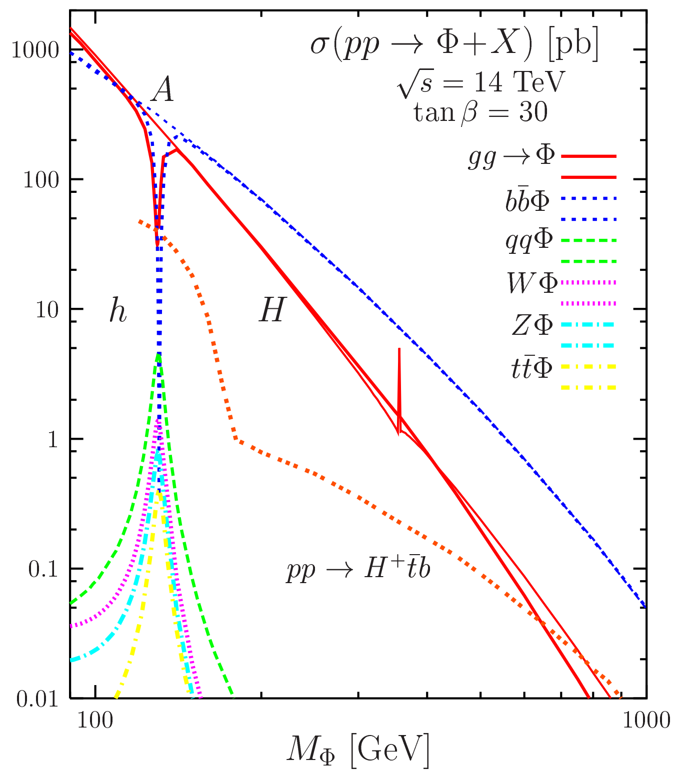
Note: total decay widths small....



8. MSSM Higgs at the LHC: production

Higgs production in the MSSM





What is different from the SM

(assuming heavy sparticles)

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

– rates suppressed except for $\mathrm{H_{SM}}$

– CP: no AV and qqA processes

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

- **For $\Phi = \mathrm{h/H, A}$ dominant processes:**

– $\mathrm{gg} \to \Phi$ with contribution of b–quarks

– $\mathrm{gg} \to \Phi \mathrm{b\bar{b}}$ or equivalent $\mathrm{b\bar{b}} \to \Phi$

(both enhanced by a power $\tan^2\beta$)

- **For charged Higgs boson:**

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

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

Now@lHC for high tanβ values:

– h/H as in SM with $\mathrm{M_h}$ =115–130 GeV

– H/h and A in $\mathrm{gg, b\bar{b}} \to \Phi \to \tau^+\tau^-$

– $\mathrm{H^\pm}$ in $\mathrm{t} \to \mathrm{H^+b}$ with $\mathrm{H^+} \to \tau^+\nu$

8. MSSM Higgs at the LHC: production

At the lHC: good chances at high tanβ

For CP–odd like Higgs $\Phi = \mathrm{A, h/H}$

$$\mathrm{gg} \to \Phi \to \tau^+\tau^-$$

(with only b–loop taken into account)

$$\mathrm{b\bar{b}} \to \Phi \to \tau^+\tau^-$$

(equivalent to pp→bbΦ with lost b's)

Large production rates at tan$\beta \gg 1$:

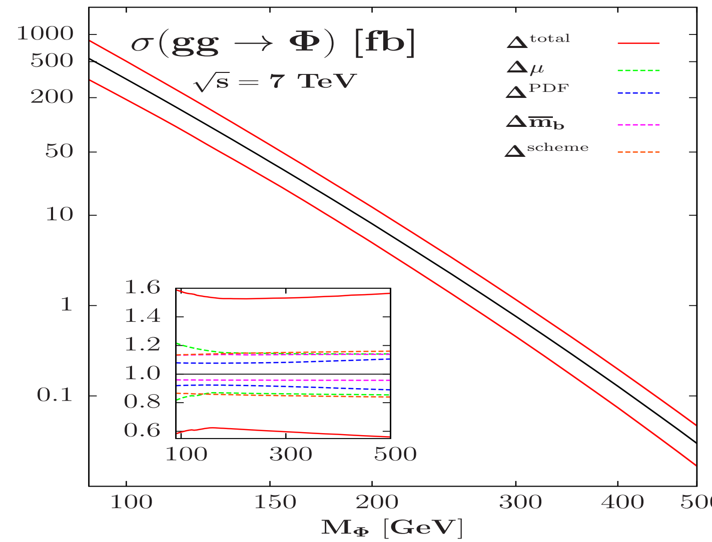
$$\sigma(\Phi) = 2\tan^2\beta \times \sigma(\mathrm{A_{SM}})$$

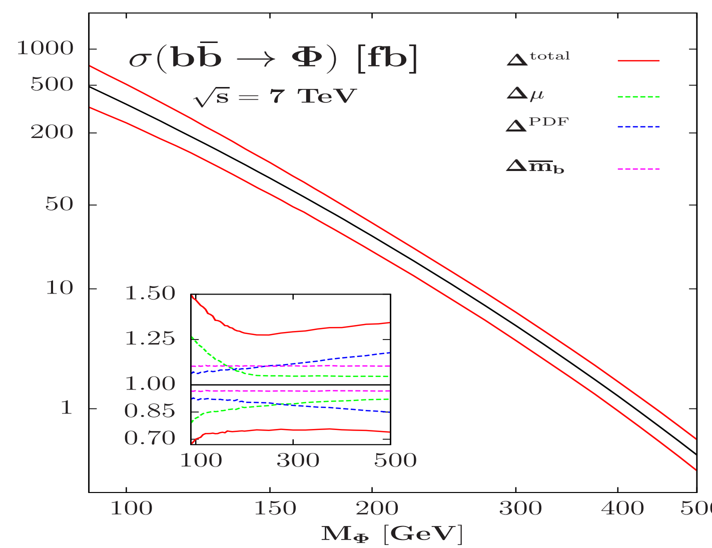
(chiral symmetry holds for $\mathrm{M_\Phi} \gg \mathrm{m_b}$)

It reduce then to a QCD problem:

- known higher order corrections
- but rather large QCD uncertainties:

– renorm/fact. scale dependence
– renor. scheme dependence for $\mathrm{m_b}$
– PDF uncertainties (at high–x)
– parametric errors from $\mathrm{m_b}, \alpha_s$

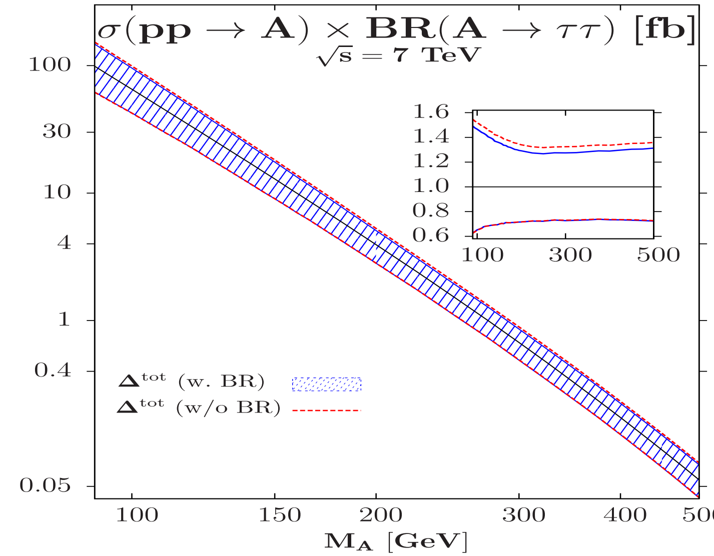




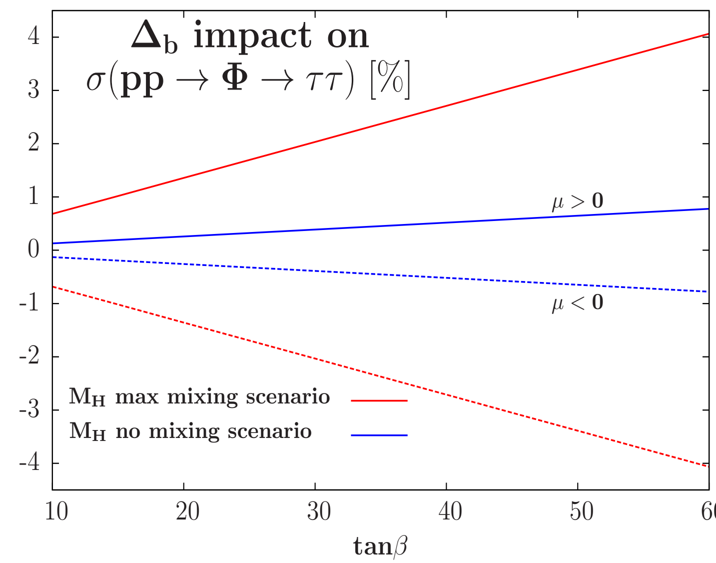
$\Rightarrow \pm 30\%$ theoretical uncertainty in combined $\mathrm{b\bar{b}} + \mathrm{gg} \to \Phi \to \tau^+\tau^-$

8. MSSM Higgs at the LHC: production

Combine the gg and bb fusion channels:
easy for inclusive search (e.g. no b–tag)
$\Rightarrow$ just sum of xsections/uncertainties
Multiply by the branching $\Phi \to \tau\tau$ ratio
BR$(\tau\tau) \approx \Gamma(\Phi \to \tau\tau)/\Gamma(\Phi \to bb)$
$\Rightarrow$ parametric errors cancel out
$\Rightarrow$ error on $\sigma \times$BR $<$ error on σ



There are also large SUSY corrections!
– dominant one from $\lambda_b \to \lambda_b(1+\Delta_b)$
– $\Delta_b \approx \frac{\alpha_s}{\pi}\mu\tan\beta/\max(\tilde{m}_g, \tilde{m}_b)$
– large at high tanβ and/or high μ
– large EW corrections also present
$\Rightarrow$ only effect of $\neq$ SUSY scenarii!
Affect both $\sigma(\Phi)$ and BR($\Phi \to \tau\tau$)
Most of it cancels in product $\sigma\times$ BR
$\Rightarrow$ effect negligible comp. QCD...



8. MSSM Higgs at the LHC: production

CMS/ATLAS searches with 36 pb^{-1}

– $\mathrm{pp} \to \mathrm{h, H, A} \to \tau\tau + \mathrm{X}$

– completely inclusive/no b–tagging

– one $\tau \to \mathrm{had}$ and one $\tau \to \ell$

– also subleading channel $\tau\tau \to e\mu$

– main background $\mathrm{pp} \to \mathrm{Z} \to \tau\tau$

– important to reconstruct $\mathrm{M}_{\tau\tau}$ peak

No excess in $\sigma(\mathrm{pp} \to \tau\tau)$ vs SM

To be interpreted in the MSSM case

$\Rightarrow$ **strong limits in $[\mathrm{M_A}, \tan\beta]$ plane**

already more stringent than Tevatron...

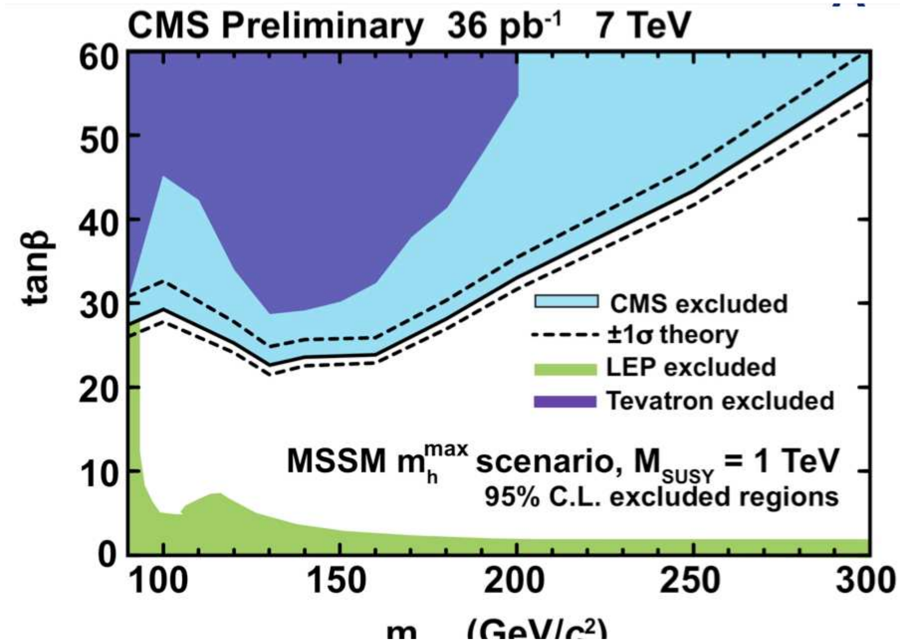
Note:

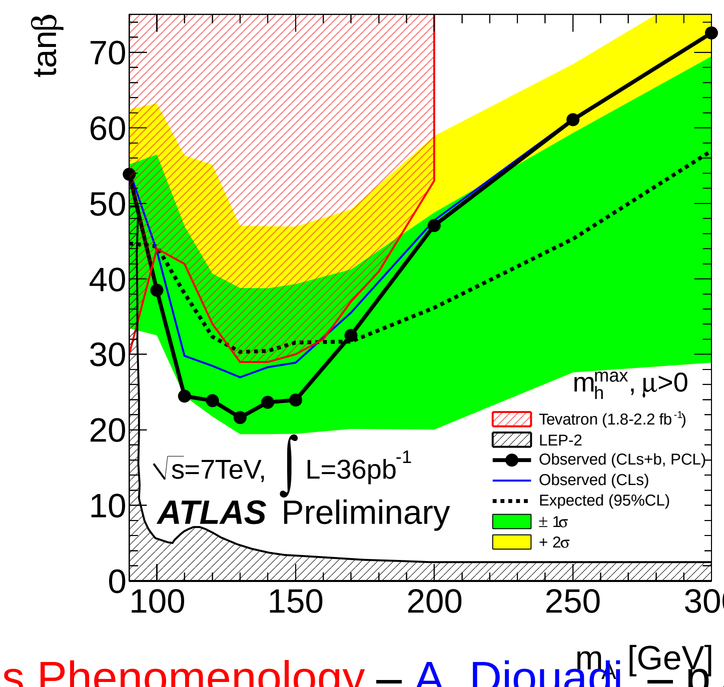
– results shown for max mixing scenario

– smaller TH uncertainties than above...

– excludes tan$\beta \lesssim$20 for $\mathrm{M_A} \approx 130$ GeV

– can be used in SM case!





8. MSSM Higgses at the LHC: detection

The lighter Higgs boson:

same as in the SM for $M_h \lesssim 140$ GeV

(in particular in the decoupling regime)

$$gg \to h \to \gamma\gamma, WW^*$$

$$pp \to hqq \to qq\gamma\gamma, qq\tau\tau, qqWW^*$$

The heavier neutral Higgses:

same production/decays for H/A in general

$$pp \to b\bar{b} + H/A \to b\bar{b} + \tau\tau/\mu\mu$$

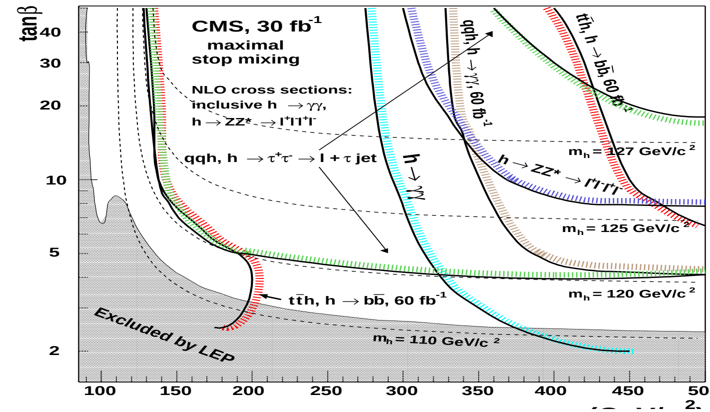
(as in SM for H in anti-decoupling regime).

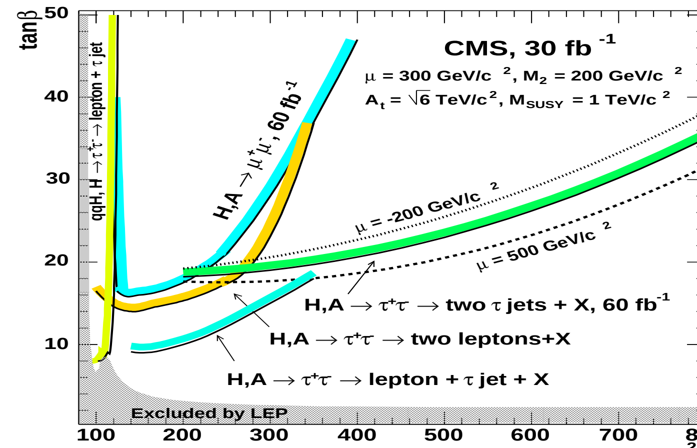
The charged Higgs:

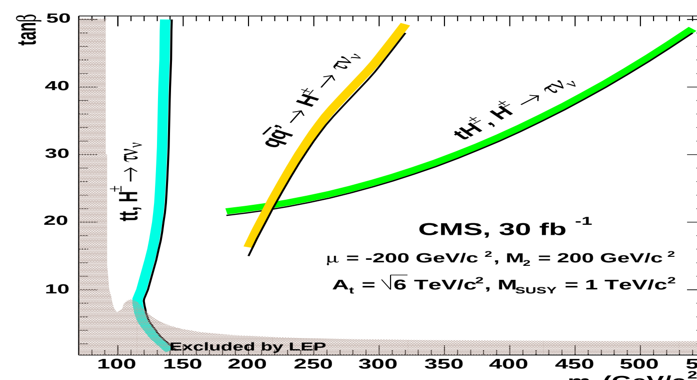
$$t \to bH^- \to b\tau\nu \text{ for } M_H \lesssim m_t$$

$$gb \to tH^+ \to t\tau\nu \text{ for } M_H \gtrsim m_t$$

reach depends on M_A and tanβ

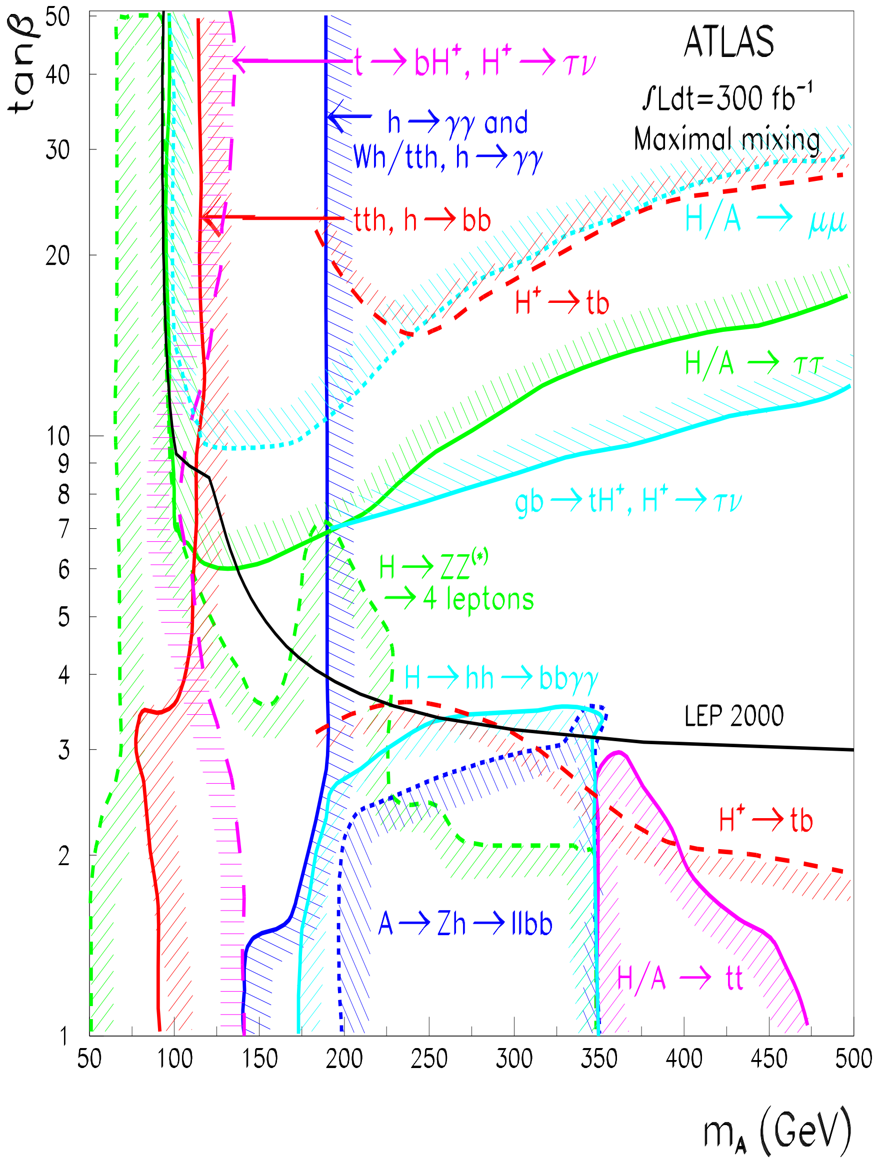


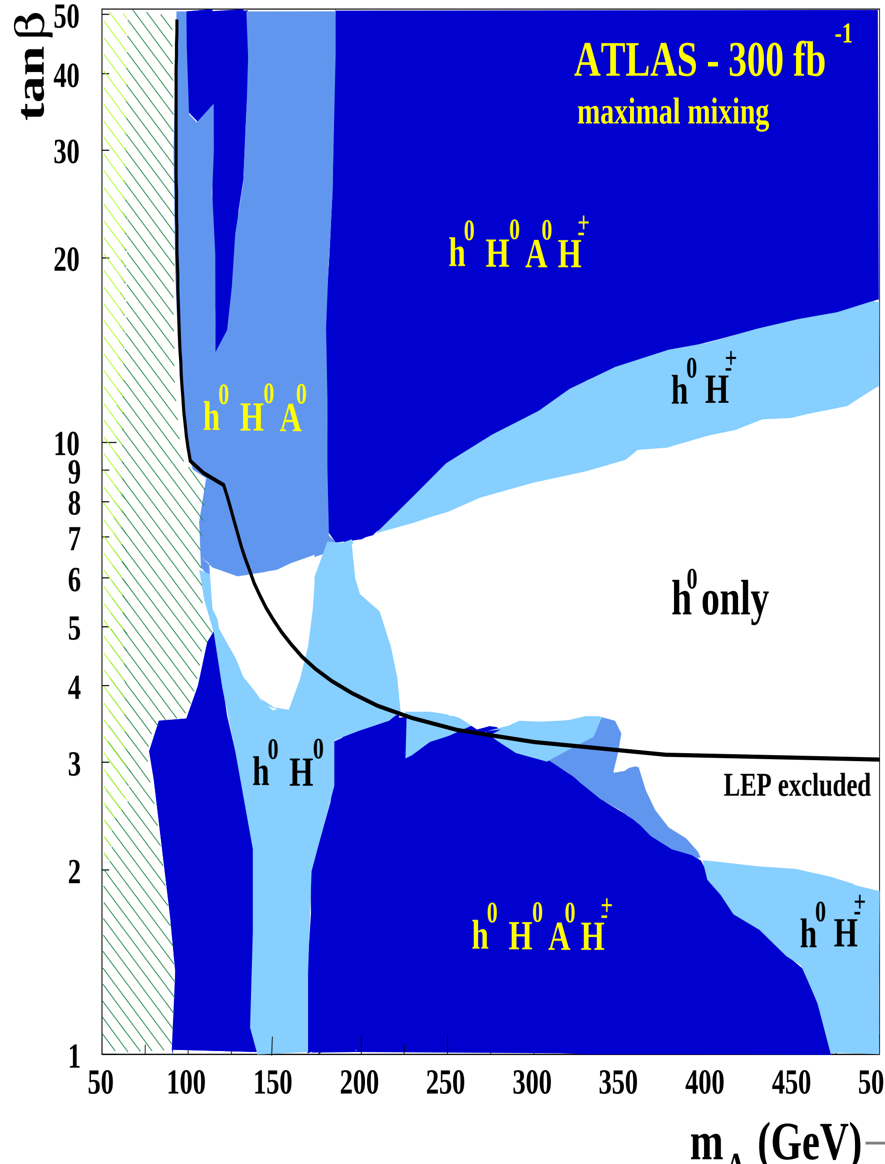




8. MSSM Higgses at the LHC: detection

Largely outdated but still telling......





8. MSSM Higgses at the LHC: measurements

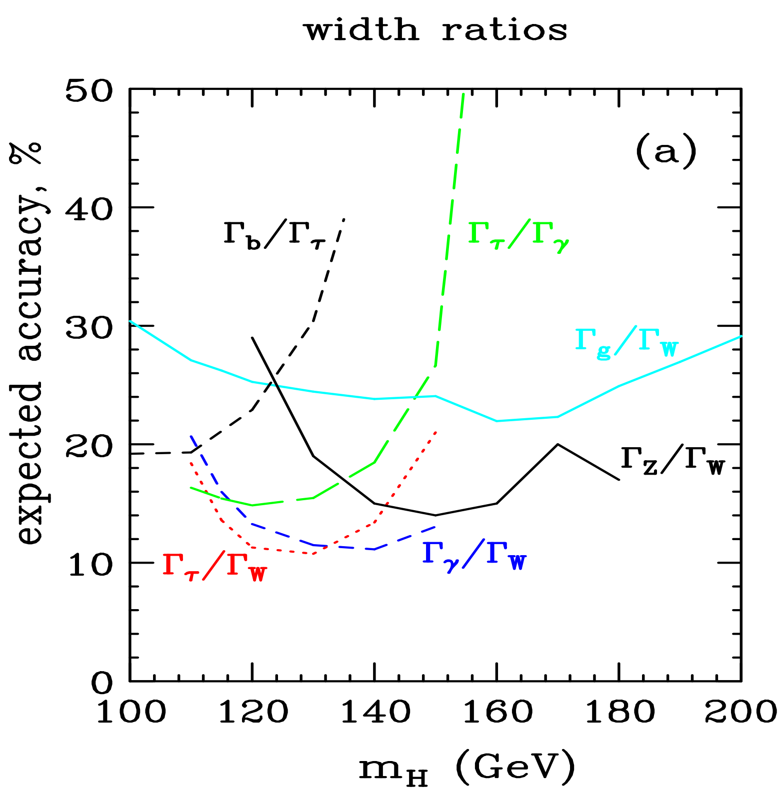
Lightest Higgs: as in SM

Higgs mass $\mathrm{h} \to \gamma\gamma, \mathrm{ZZ}^*$

Higgs couplings from $\sigma\times$ BR

Higgs spin+CP numbers: hard

Higgs self-couplings hopeless...

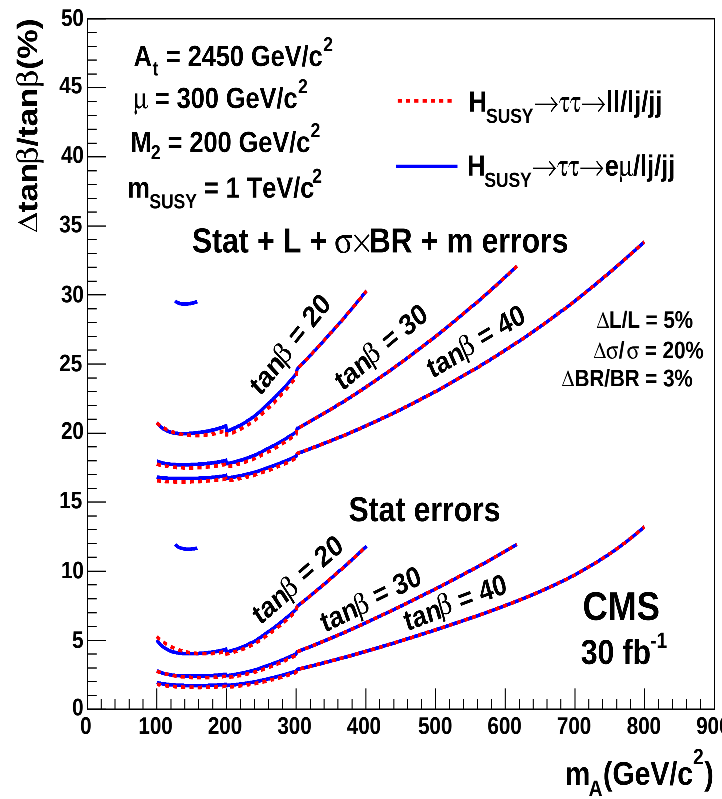


The heavy Higgsses

Masses from $\mathrm{H/A} \to \mu^+\mu^-$

$\tan\beta$ in $\mathrm{pp} \to \mathrm{H/A} + \mathrm{b\bar{b}}$

H/A separation very difficult



9. SUSY Higgsses: special scenarios

However: life can be much more complicated even in the MSSM

- **There are scenarii where searches are different from the SM case:**

– The intense coupling regime: h,H,A almost mass degenerate....

- **SUSY particles might play an important role in production/decay:**

– light $\tilde{\mathrm{t}}$ loops might make $\sigma(\mathrm{gg}\to\mathrm{h}\to\gamma\gamma)$ smaller than in SM.

– Higgsses can be produced with sparticles ($\mathrm{pp} \to \tilde{\mathrm{t}}\tilde{\mathrm{t}}^*\mathrm{h}$,..).

– Cascade decays of SUSY particles into Higgs bosons....

- **SUSY decays, if allowed, might alter the search strategies:**

– $\mathrm{h} \to \chi_1^0\chi_1^0, \tilde{\nu}\tilde{\nu}$ are still possible in non universal models...

– Decays of $\mathrm{A}, \mathrm{H}, \mathrm{H}^{\pm}$ into $\chi_i^{\pm}, \chi_i^0$ are possible but can be useful...

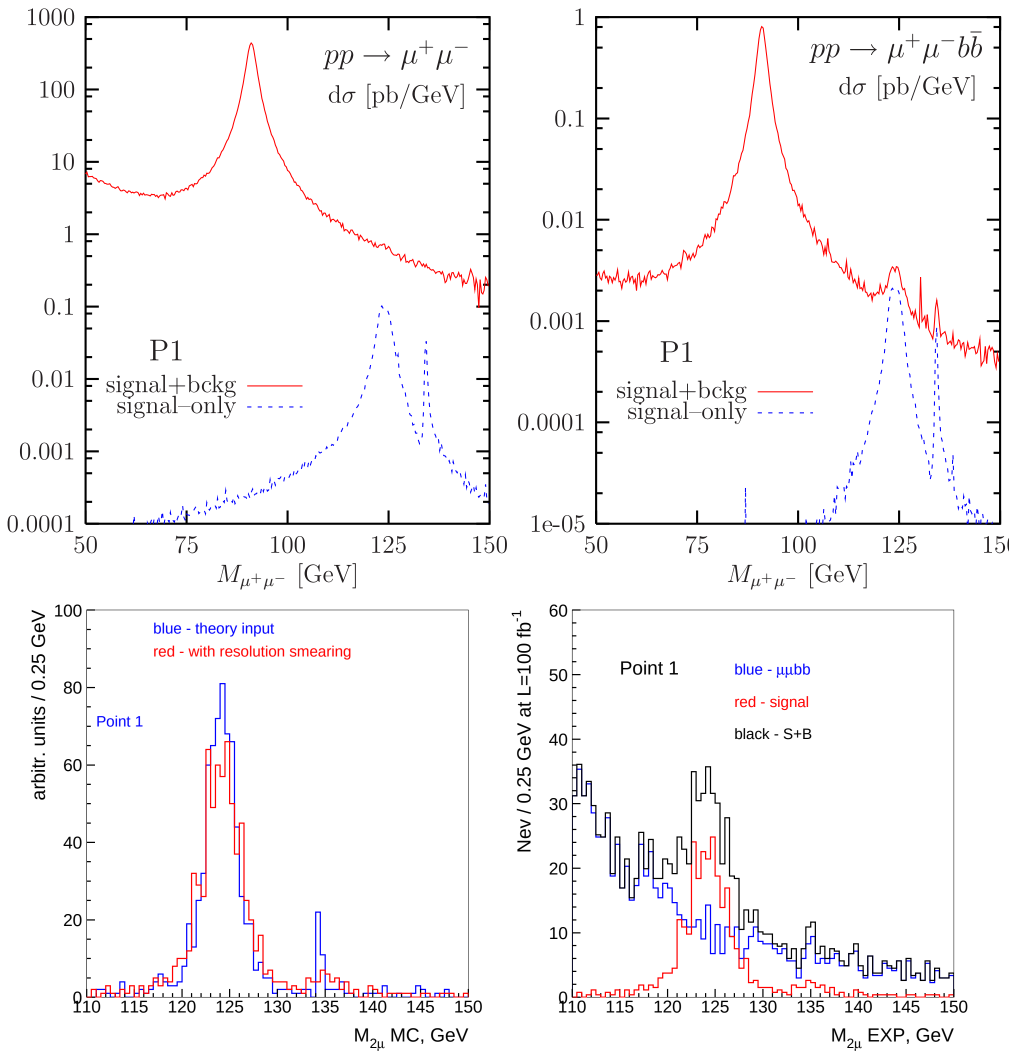
Life can be even more complicated in extensions of the MSSM

Be prepared for the unexpected!

9. SUSY Higgsses: special scenarios

- **There are scenarii where searches are different from the SM case:**

– The intense coupling regime: h,H,A almost mass degenerate....



9. SUSY Higgsses: special scenarios

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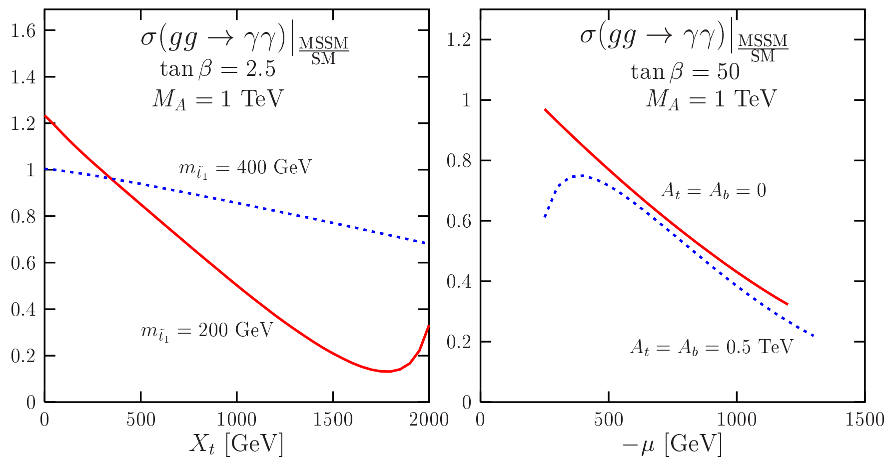
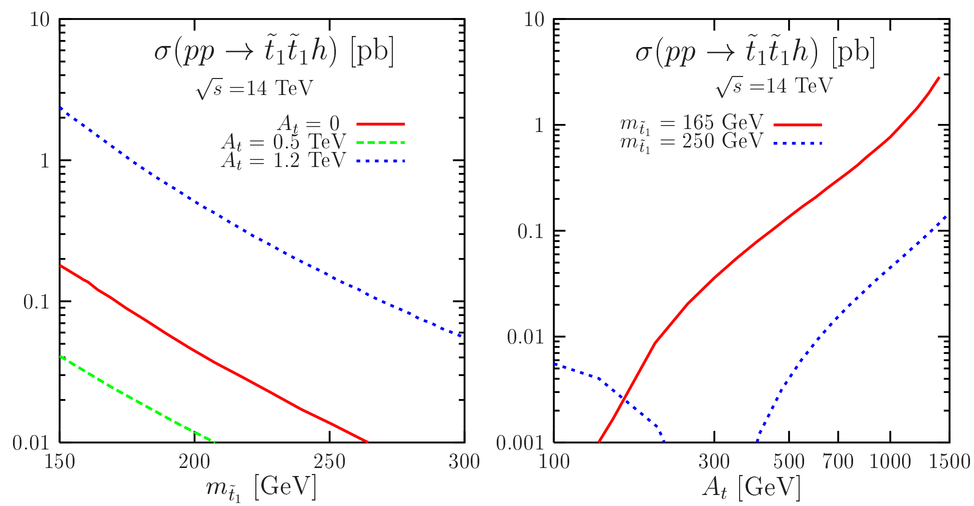
– light $\tilde{\mathrm{t}}$ loops might make $\sigma(\mathrm{gg}\to\mathrm{h}\to\gamma\gamma)$ smaller than in SM.



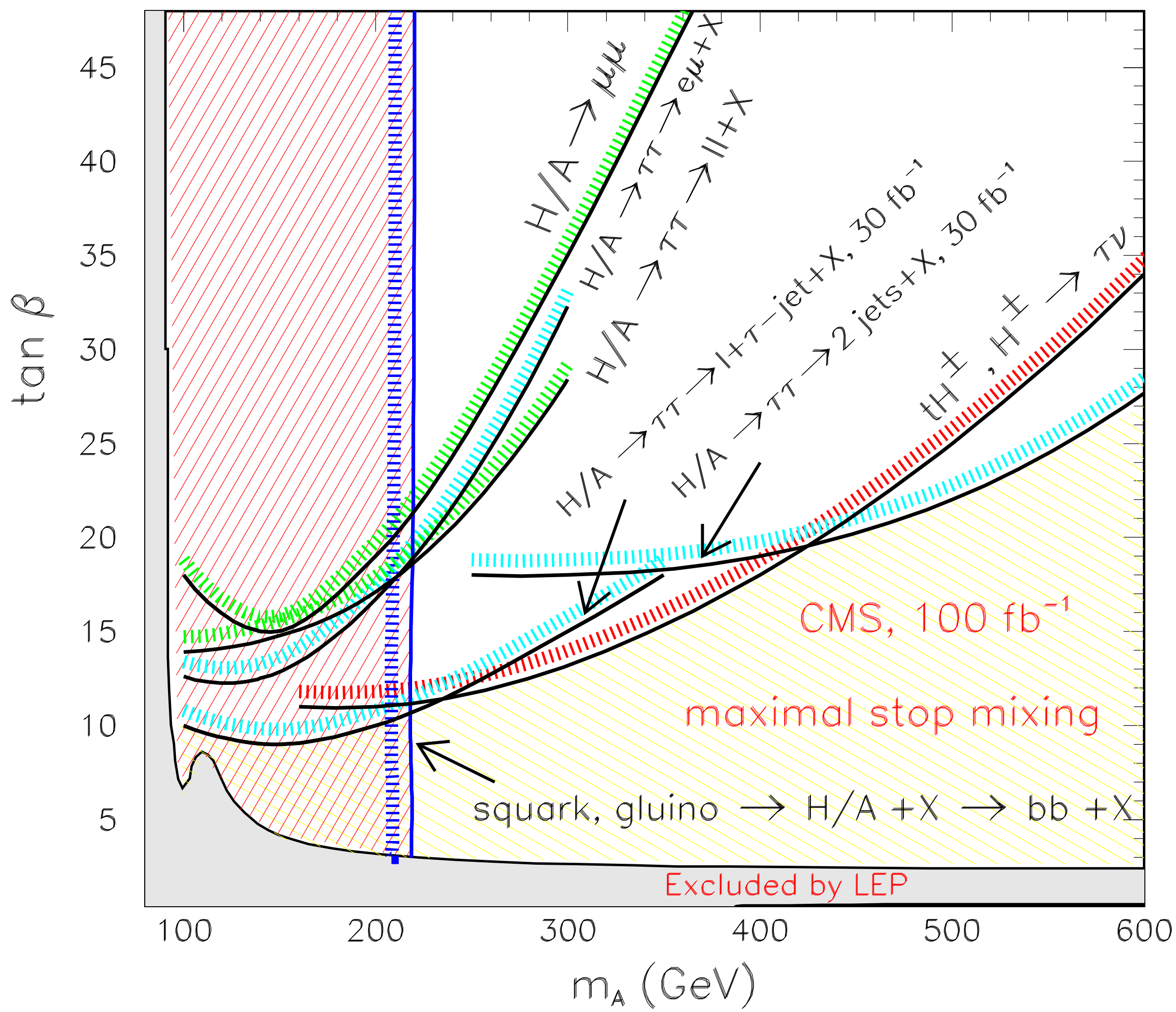
– Higgses can be produced with sparticles ($\mathrm{pp}\to\tilde{\mathrm{t}}\tilde{\mathrm{t}}^{*}\mathrm{h}$,..).



9. SUSY Higgsses: special scenarios

- **SUSY particles might play an important role in production/decay:**

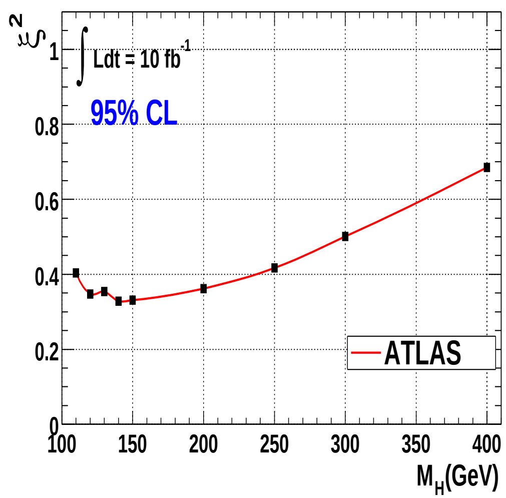
– Cascade decays of SUSY particles into Higgs bosons....

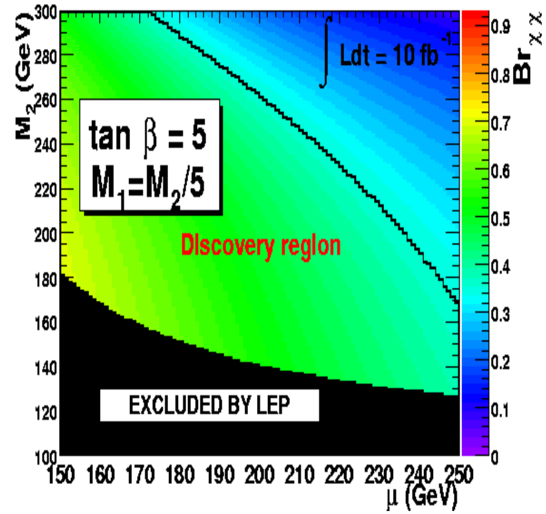


9. SUSY Higgses: special scenarios

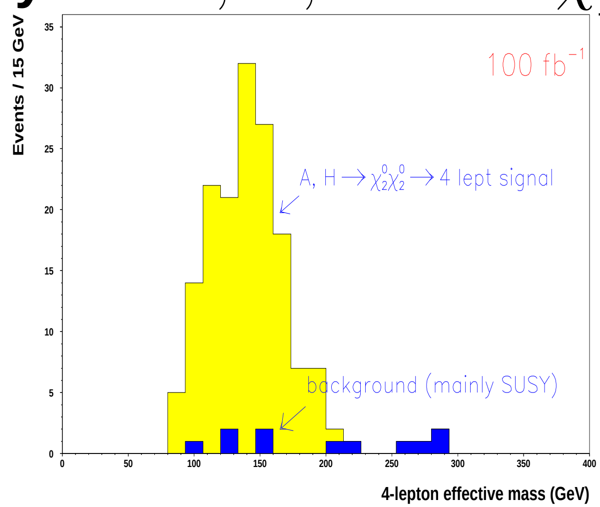
- **SUSY decays, if allowed, might alter the search strategies:**

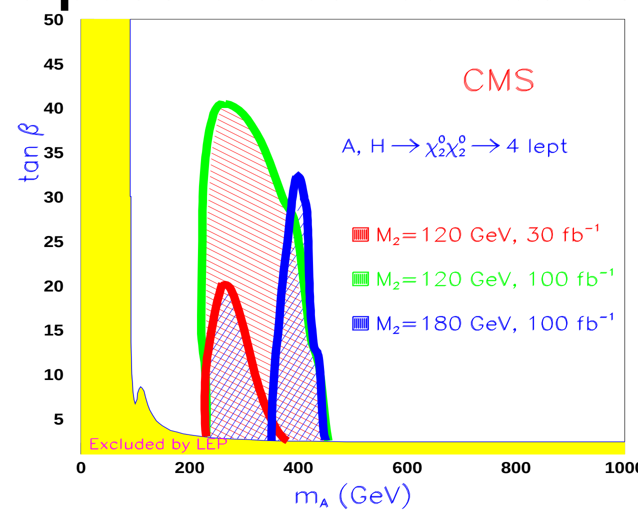
– $\mathrm{h} \to \chi_1^0\chi_1^0, \tilde{\nu}\tilde{\nu}$ **are still possible in non universal models...**





– **Decays of** $\mathrm{A, H, H^\pm}$ **into** $\chi_i^\pm, \chi_i^0$ **are possible but can be useful...**





9. SUSY Higgsses: special scenarios

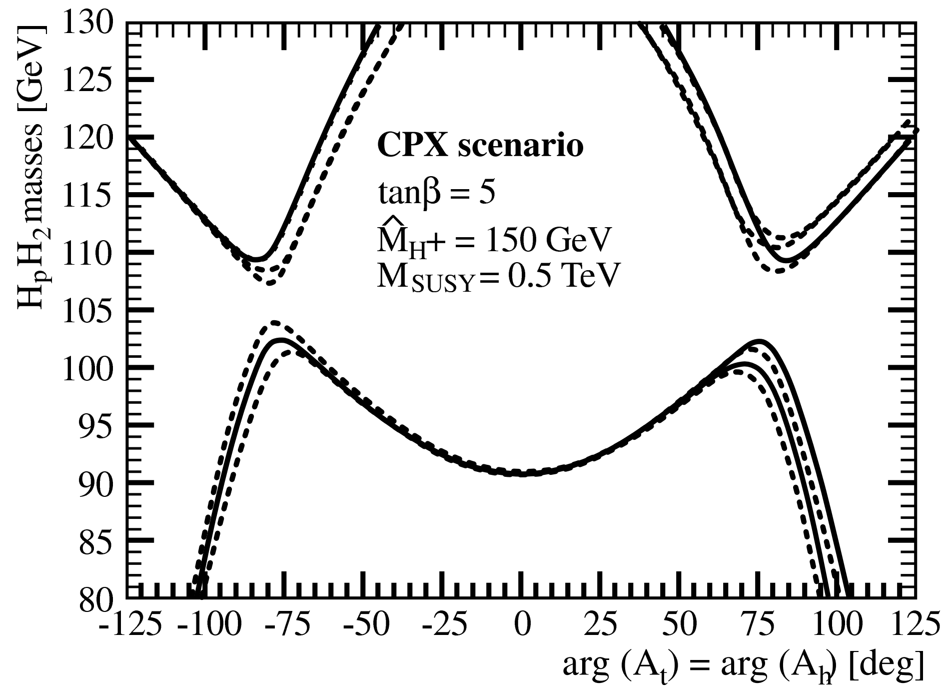
Life can be even more complicated in extensions of the MSSM

We can allow for some amount of CP–violation in eg. M_i, μ and A_f

Higgs sector: CP–conserving at tree level $\Rightarrow$ CP–violating at one–loop

Good to address the issue of baryogenesis at the electroweak scale....

- **h, H,A are not CP definite states and h_1, h_2, h_3 CP mixtures**
- **determination of Higgs spectrum slightly more complicated,**
- **possibility of a light h_1 that has escaped detection at LEP2.**



9. SUSY Higgses: special scenarios

The CPX scenario:

h_1 light but weak cplgs to W,Z

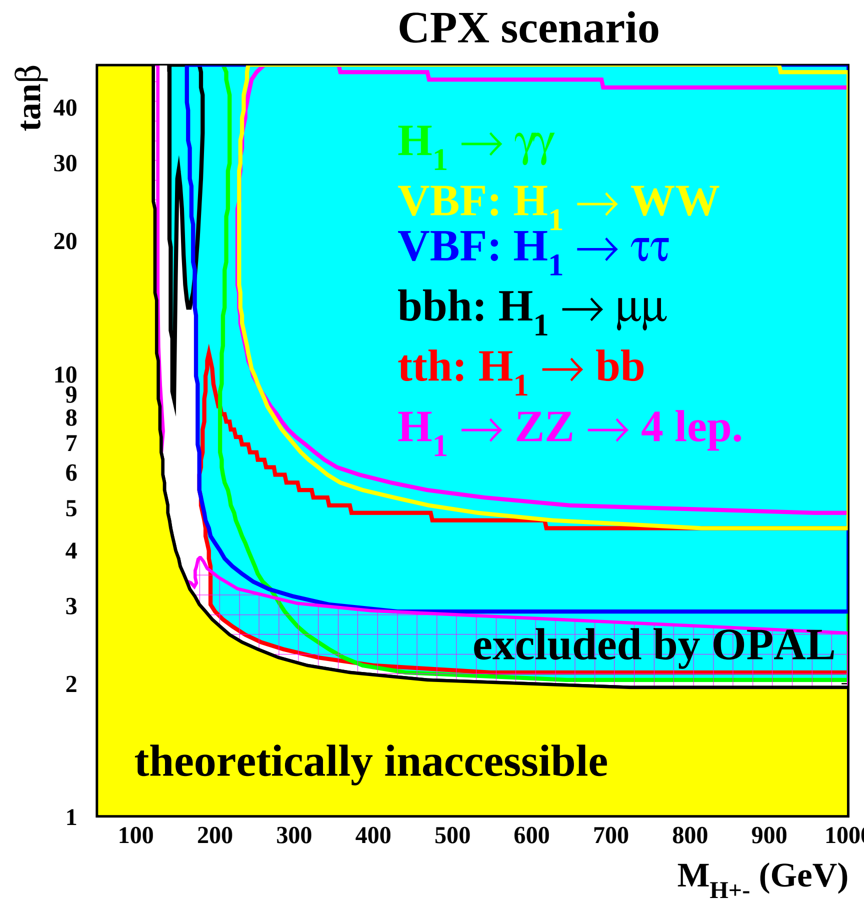
$h_2 \to h_1 h_1$ decays allowed

h_3 couplings to VV reduced...

All Higgses escape detection

Still, there is the possibility

$t \to H^+ b \text{ with } H^+ \to hW^*$



Regions of MSSM parameter space not covered by ATLAS/CMS:

more work is still needed....

9. SUSY Higgsses: special scenarios

The next-to-minimal SSM is becoming the "standard" MSSM these days..

MSSM problem: μ is SUSY-preserving but $\mathcal{O}(\mathrm{M_Z})$; a priori no reason

Solution, μ related to the vev of singlet field, $\langle \mathbf{S} \rangle \propto \mu$

NMSSM: introduce a gauge singlet in Superpotential: $\lambda \hat{\mathbf{H}}_1 \hat{\mathbf{H}}_2 \hat{\mathbf{S}} + \frac{1}{3} \hat{\mathbf{S}}$

SUSY spectrum extended by χ_5^0 and two neutral Higgs particles $\mathbf{h_3, a_2}$

- **additional parameters enter in Higgs masses and couplings**

  less constrained model, more flexibility, ...

- **the bound on lightest Higgs boson mass is higher than in MSSM**

  less fine-tuning is needed to cope with LEP..

- **possibility of a light Higgs which has escaped detection at LEP2**

possibility of a light Higgs which has escaped detection at LEP2

  rich phenomenology: low energy constraints, DM, ...

- **Note: constrained NMSSM, less freedom than in mSUGRA ...**

9. SUSY Higgses: special scenarios

The NMSSM with universal boundary conditions at GUT scale:

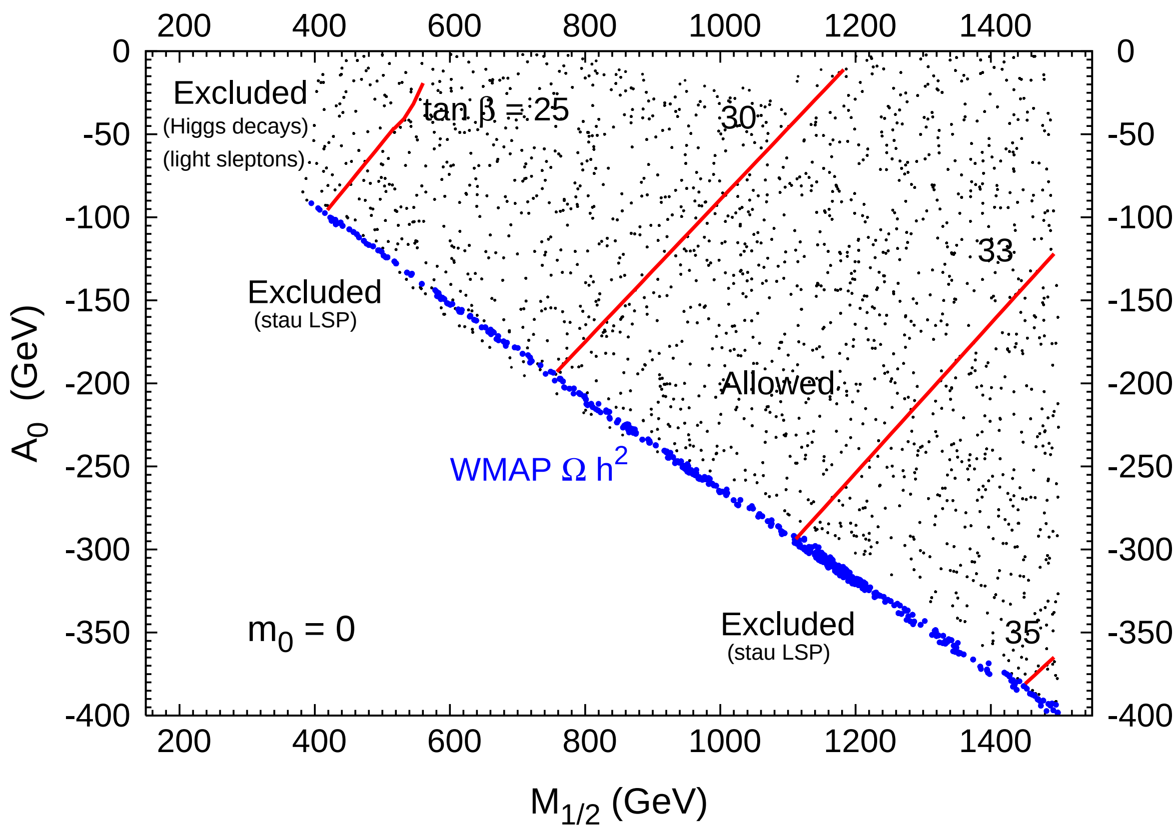
In principle: $\mathbf{M_{1/2}, m_0, A_0, \lambda, \tan\beta}$ **as free parameters**

With constraints: proper EWSB+LEP Higgs+low energy+ WMAP

only one cNMSSM free parameter: $\mathbf{m_0 \sim 0}$ **and** $\lambda \lesssim \mathbf{0.01}$

The parameters $\mathbf{A_0}$ **and** $\tan\beta$ **are related to** $\mathbf{M_{1/2}}$

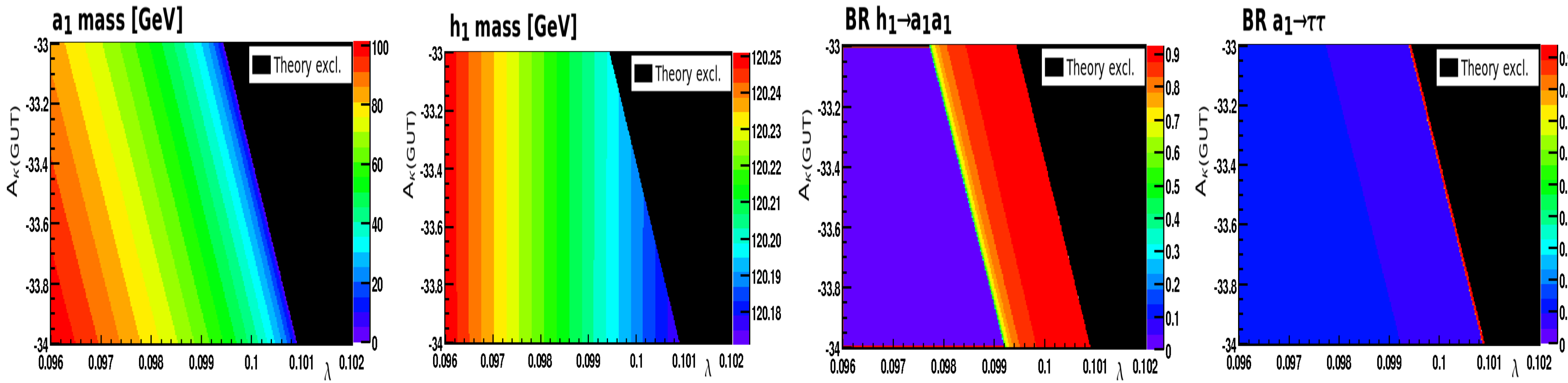
Ellwanger, Teixeira, AD (2008)



9. SUSY Higgsses: special scenarios

But life can be even more complicated with LHC Higgs searches:

the possibility of missing all Higgs bosons is not yet ruled out!



Recently, some benchmark scenarios for NMSSM Higgs searches have been proposed in Les Houches:

- h_1 **is SM–like and** a_1 **light:** $h_1 \to a_1 a_1$ **with** $a_1 \to b\bar{b}$ **and/or** $\tau^+\tau^-$
- h_2 **is SM–like and** h_1 **light:** $h_2 \to h_1 h_1$ **with** $h_1 \to b\bar{b}$
- **All Higgs are light (NMSSM ICR): reduced couplings to VV, etc...**

9. SUSY Higgses: special scenarios

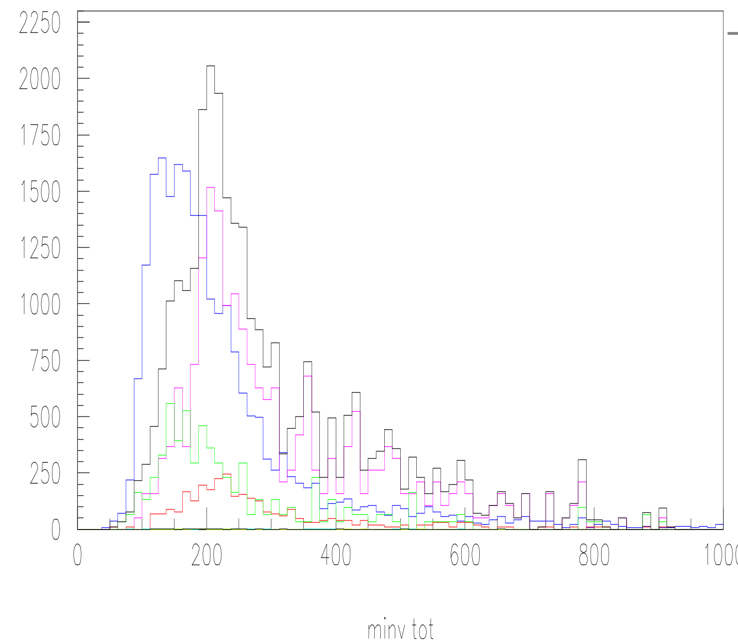
Higgs $\to$ Higgs+Higgs $\to$ $4\mathrm{b}, 2\mathrm{b}2\tau$

searches very difficult at the LHC:

$pp \to qq \to\to W^*W^*qq \to h_1qq$

——– $h_1 \to a_1a_1 \to b\bar{b}\tau\tau \times 500$.

——– total background.



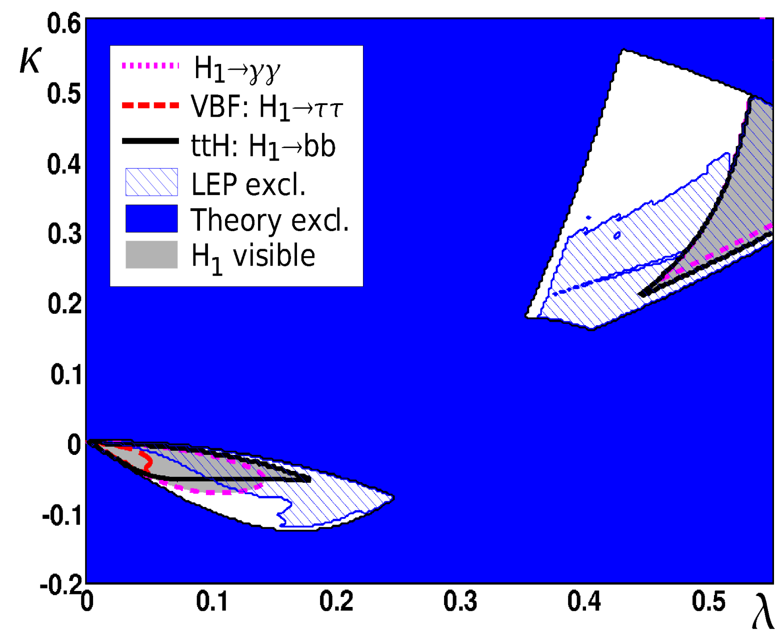
Higgs $\to$ Higgs+Higgs $\to$ $4\tau \to 4\ell\mathrm{X}$

also difficult but detection possible

Example of scan for light h_1

using VBF + all h_1 decay channels

(same for all Higgsses can be done)

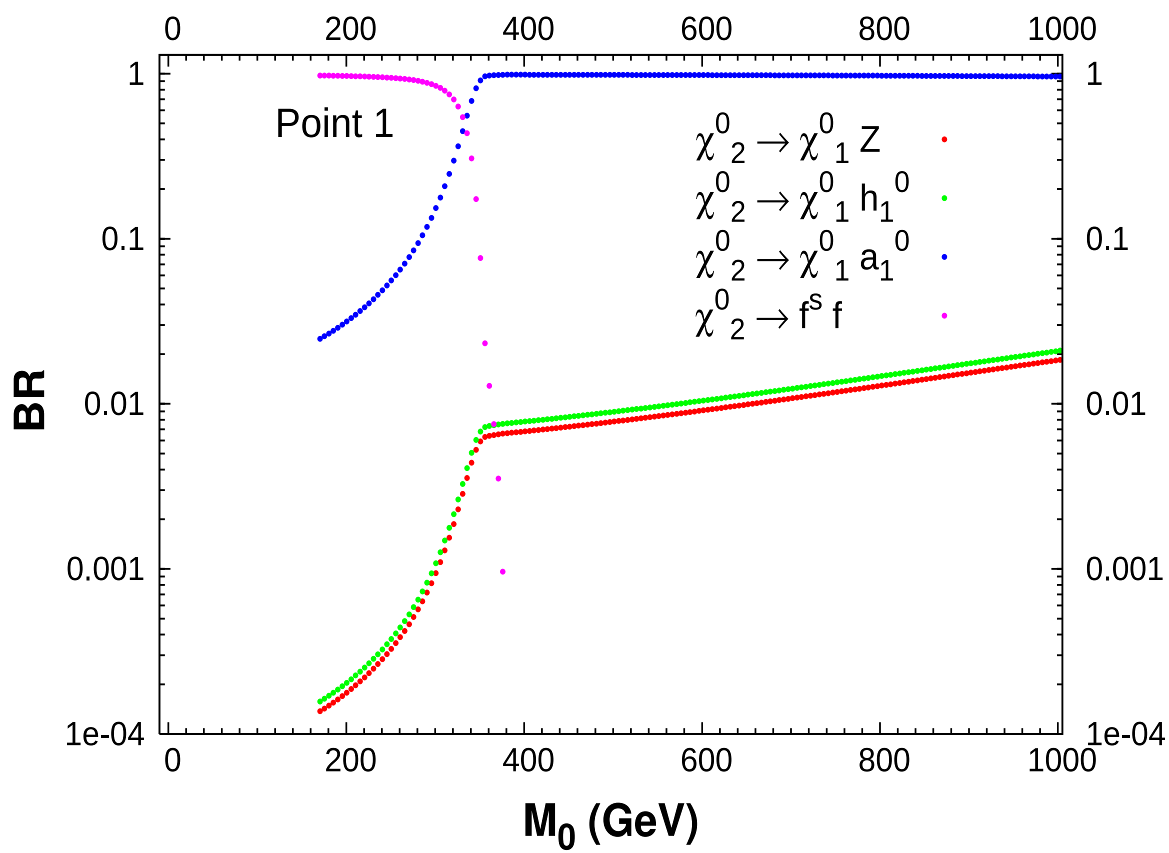


9. SUSY Higgsses: special scenarios

A possible rescue in both the CPV MSSM and NMSSM might come from SUSY particle cascade decays into Higgs bosons. In particular:

$$\mathbf{pp \to \tilde{q}\tilde{q}, \tilde{g}\tilde{g}, \tilde{g}\tilde{q} \to \chi + X \;\text{with}\; \chi_2^0 \to \chi_1^0 + Higgs}$$

Example for one of the NMSSM benchmark points with light a_1:



9. BSM Higgsses: special scenarios

There are many scenarios in which a Higgs boson would decay invisibly

- In MSSM, Higgs $\rightarrow \chi_1^0\chi_1^0, \tilde{\nu}\tilde{\nu}$, etc.. as already discussed.
- In MSSM with $\mathrm{R}\!\!\!/_{\mathrm{p}}$: Higgs $\rightarrow \mathrm{JJ}$ could be dominant.
- The SM when minimaly extended to contain a singlet field (which decouples from f/V), $\mathrm{H} \rightarrow \mathrm{SS}$ can be dominant
- In large extra dimensions H mixing with graviscalars.

... or very different couplings to fermions and bosons...

- Radion mixing in warped extra dimension models: supressed f/V couplings and Higgs decays to radions
- Presence of new quarks which alter production

... Many possible surprises/difficult scenarios.......