Physics at the LHC

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- **Standard Physics at the LHC**
- **The SM Higgs at the LHC**

1. SM Higgs: constraints

2. Higgs decays

3. Higgs production at the LHC

3. Measurement of Higgs properties

- **SUSY and SUSY–Higgs at the LHC**

1. The Higgs in the SM

To generate particle masses in SM in a gauge invariant way: SSB

$\Rightarrow$ introduce a doublet of complex scalar fields $\Phi = \binom{\phi^+}{\phi^0}$ with $Y_\Phi = 1$

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

$\mu^2 < 0 : \Phi$ develops a vev: $\langle 0|\Phi|0\rangle = \frac{1}{\sqrt{2}}\binom{0}{v}$, $v = (-\frac{\mu^2}{\lambda})^{1/2}$=246 GeV

$\Rightarrow$ 3 degrees of freedom for $W^\pm_L, Z_L$ and thus $M_{W^\pm}, M_Z; M_\gamma = 0$

For fermion masses, use <u>same</u> doublet field Φ and its <u>conjugate</u> field

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

Residual degree correspond to the spin–zero Higgs particle, H.

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

Higgs couplings derived the same way as the particle masses:

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

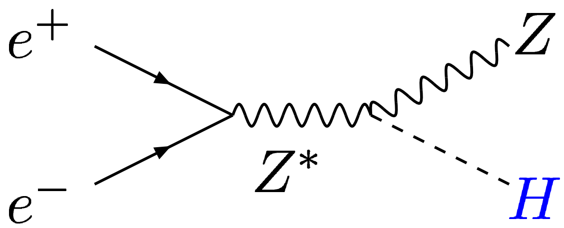
$$\Rightarrow g_{Hff} = i m_f/v \;, \; g_{HVV} = -2i M_V^2/v \;, \; g_{HHVV} = -2i M_V^2/v^2$$

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

1. Constraints on M_H: experiment

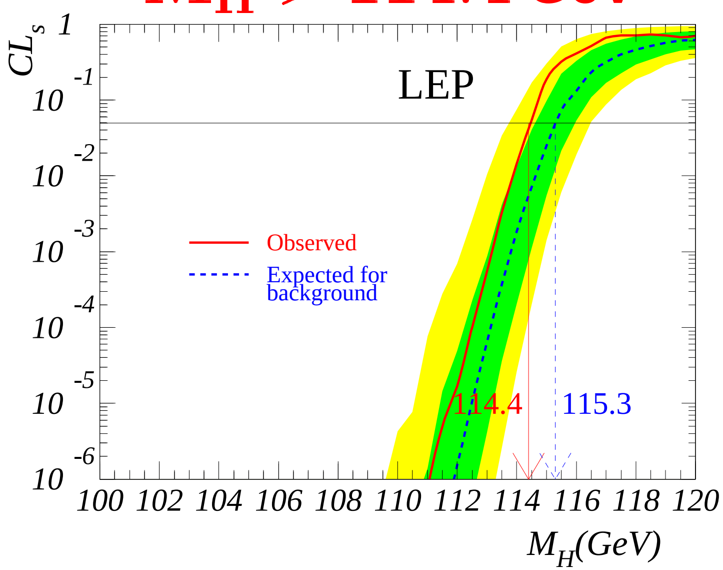
Direct searches at LEP:

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



We have a limit at 95% CL:

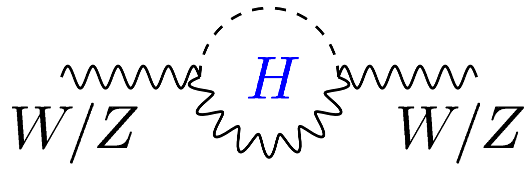
$M_H > 114.4$ **GeV**



(1.7σ excess at $M_H \sim 116$ GeV)

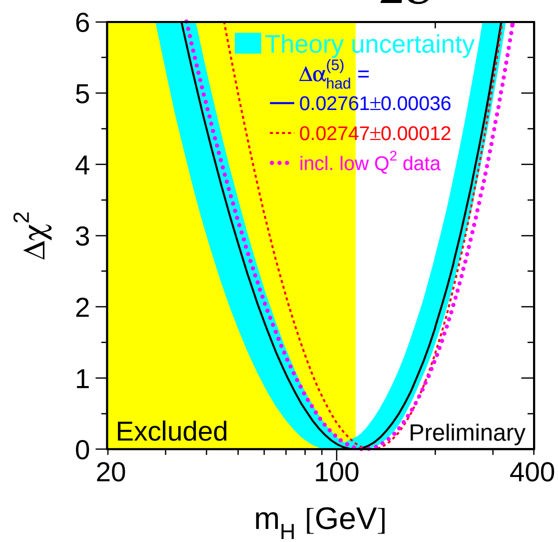
Indirect searches:

H contributes to RC to W/Z masses:



Fit the EW precision measurements:

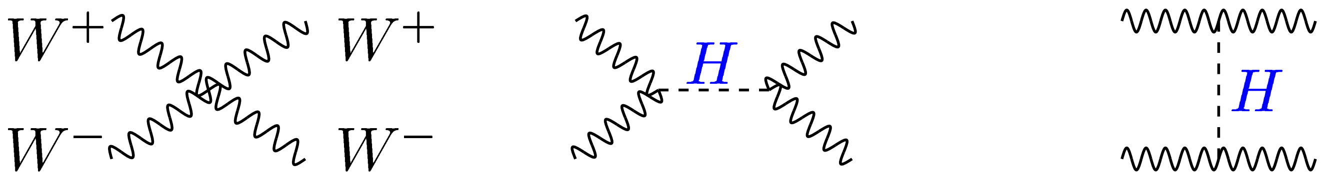
we obtain $M_H = 85^{+39}_{-28}$ GeV, or



$M_H \lesssim 200$ **GeV at 95% CL**

1. Constraints on M_H: perturbative unitarity

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



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

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

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

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

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

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

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

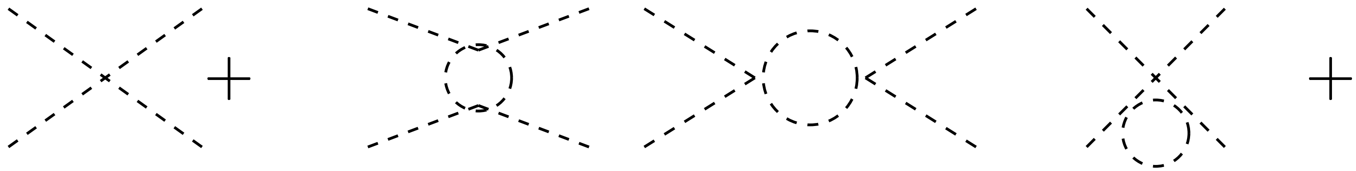
For a very heavy or no Higgs boson, we have: $\mathbf{a_0 \stackrel{s \ll M_H^2}{\longrightarrow} -\frac{s}{32\pi v^2}}$

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

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

1. Constraints on M_H: triviality

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



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

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

- 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** $Q = v\exp\left(\frac{4\pi^2 v^2}{M_H^2}\right)$.

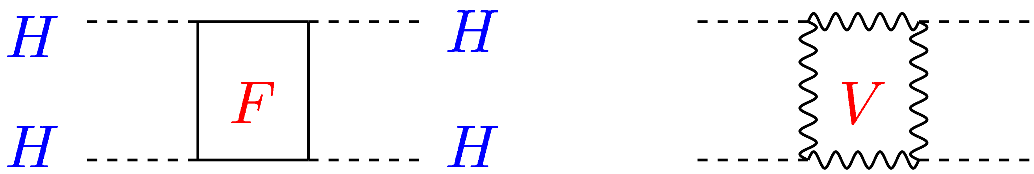
The SM is valid only at scales before λ becomes infinite:

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

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

1. 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:

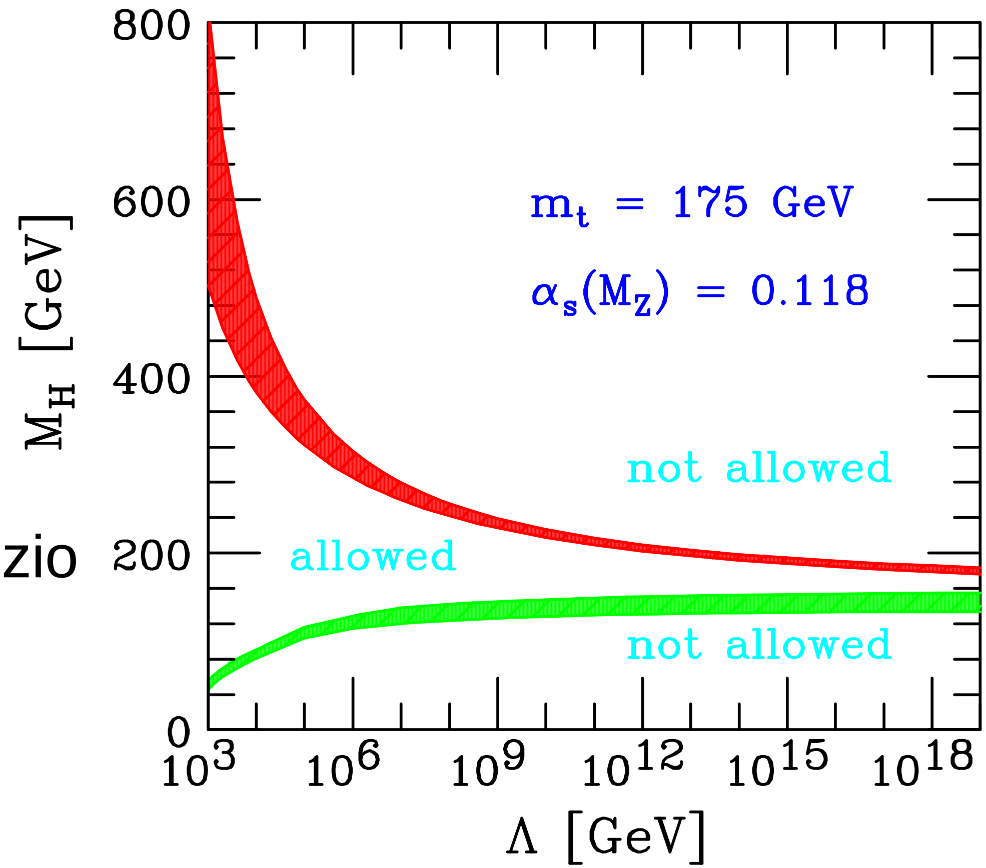
$$\lambda(Q^2) > 0 \Rightarrow M_H^2 > \frac{v^2}{8\pi^2}\left[-12\frac{m_t^4}{v^4} + \frac{3}{16}\left(2g_2^4 + (g_2^2+g_1^2)^2\right)\right]\log\frac{Q^2}{v^2}$$

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

1. Constraints on M_H: triviality+stability

Combine the two constraints and include all possible effects:

- **corrections at two loops**
- **theoretical errors**
- **experimental errors**
- **other refinements $\cdots$**



Cabibbo, Maiani, Parisi, Petronzio
Hambye, Riesselmann

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

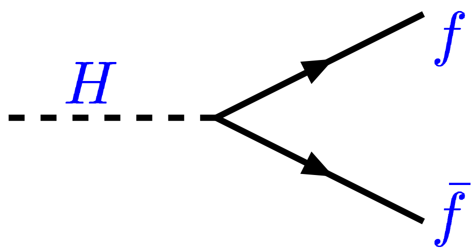
$$\Lambda_C \sim 10^{16} \, \text{GeV} \quad \Rightarrow \quad 130 \, \text{GeV} \lesssim M_H \lesssim 180 \, \text{GeV}$$

2. 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 tendancy to decay into heaviest available particle.**

Higgs decays into fermions:



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

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

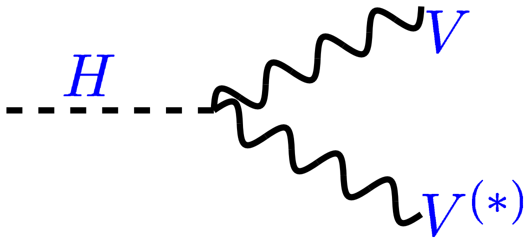
$$N_c = \text{color number}$$

- **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 (one-loop).**

2. 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:**

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

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

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

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

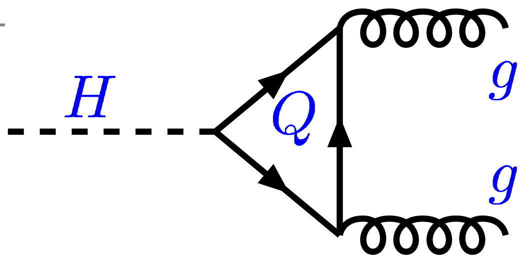
- **For a light Higgs boson:**

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

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

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

2. Higgs decays: decays into gluons



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

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

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

- Gluons massless and Higgs has no color: must be a loop decay.
- For $m_Q \rightarrow \infty, \tau_Q \sim 0 \Rightarrow A_{1/2} = \frac{4}{3} =$ 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 $m_Q \rightarrow \infty / \tau_Q = 1$ valid for $M_H \lesssim 2m_t = 350$ GeV.

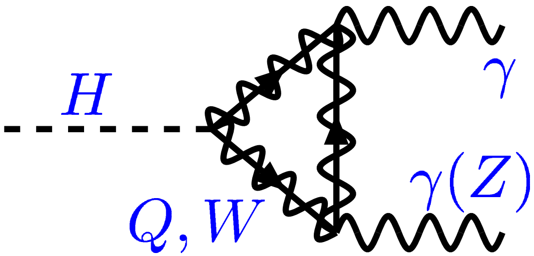
Good approximation in decay: include only t–loop with $m_Q \rightarrow \infty$. But:

- 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 $gg \rightarrow H$ very important for Higgs production in pp!

2. 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 $H \to Z\gamma$.

2. Higgs decays: branching ratios

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

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

– $\mathrm{H} \to b\bar{b}$ **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** $\gtrsim 2\mathrm{M_W}$

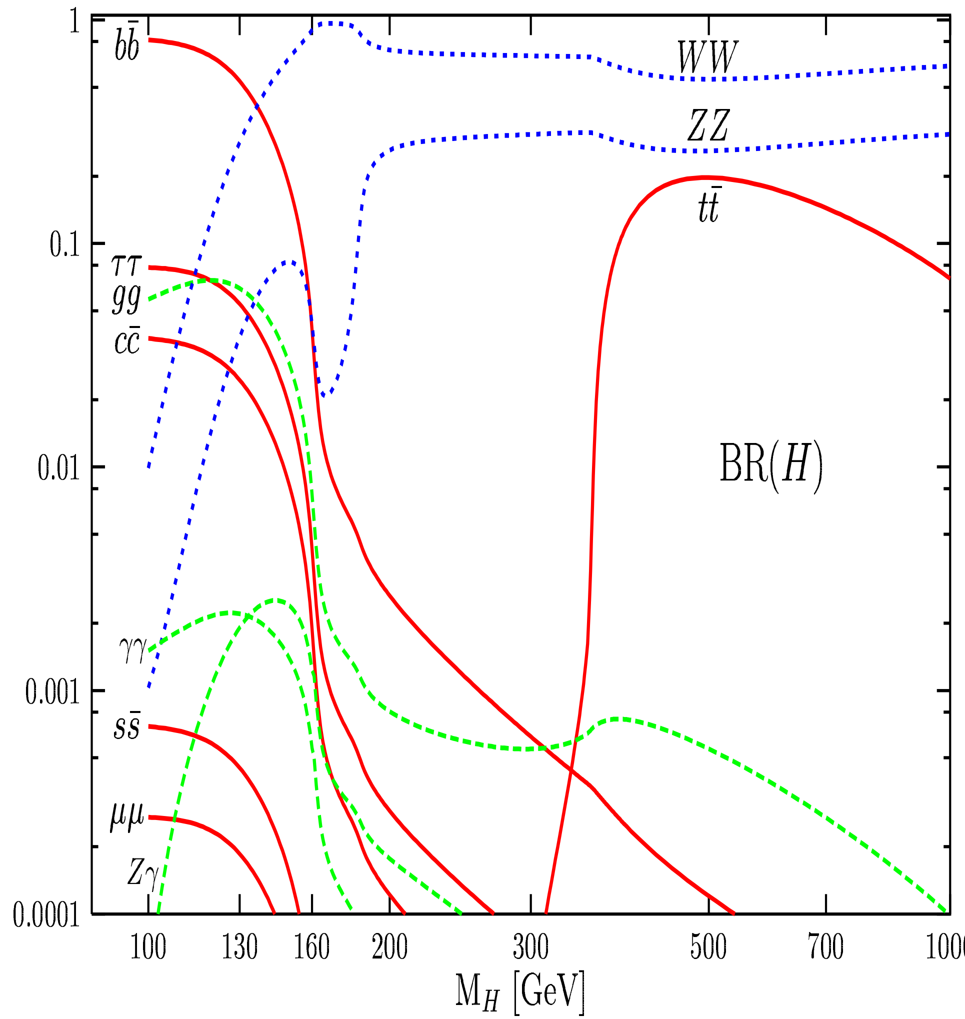
– $\mathrm{H} \to WW, ZZ$ **above (BR** $\to \frac{2}{3}, \frac{1}{3}$**)**

– $\mathrm{H} \to t\bar{t}$ **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).**



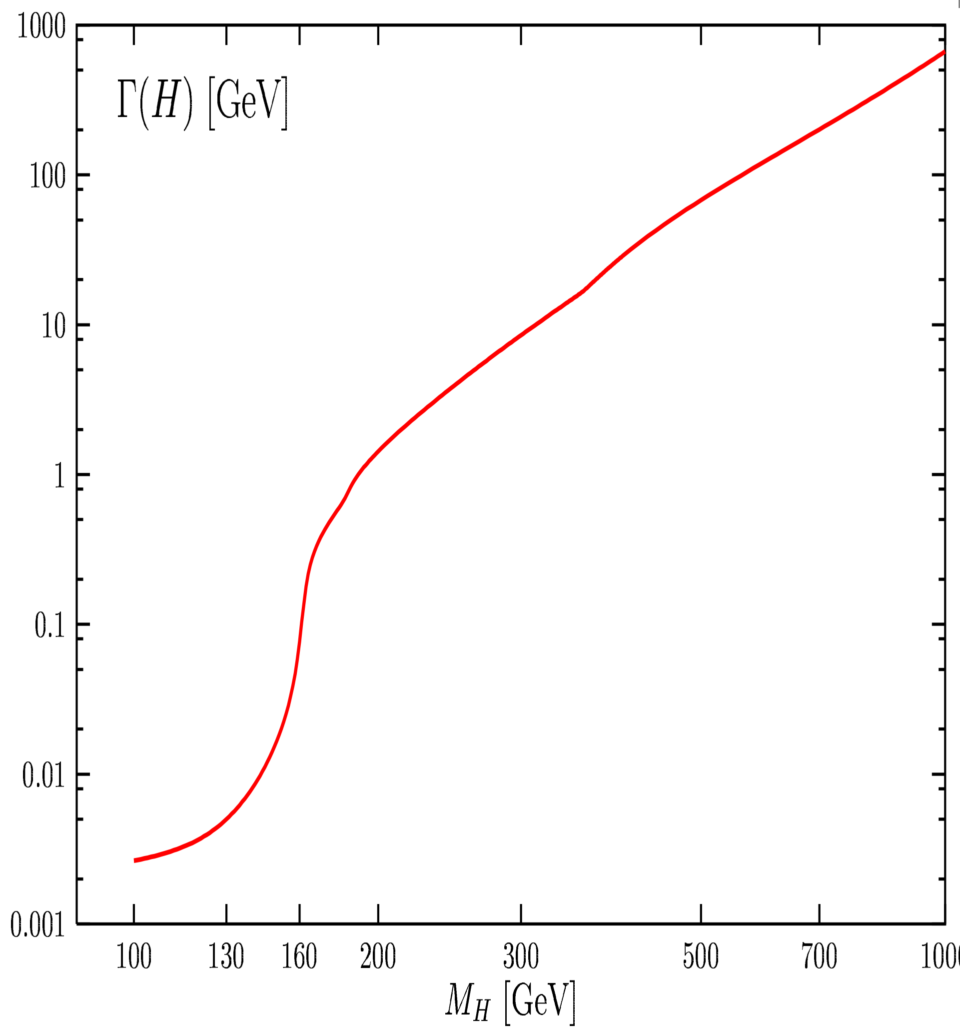
2. Higgs decays: total width

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

- **'Low mass range', $M_H \lesssim 130$ GeV:**
- $H \to b\bar{b}$ dominant, BR = 60–90%
- $H \to \tau^+\tau^-, c\bar{c}, gg$ BR= a few %
- $H \to \gamma\gamma, \gamma Z$, BR = a few permille.

- **'High mass range', $M_H \gtrsim 130$ GeV:**
- $H \to WW^*, ZZ^*$ up to $\gtrsim 2M_W$
- $H \to WW, ZZ$ above (BR $\to \frac{2}{3}, \frac{1}{3}$)
- $H \to t\bar{t}$ for high M_H; BR $\lesssim 20\%$.

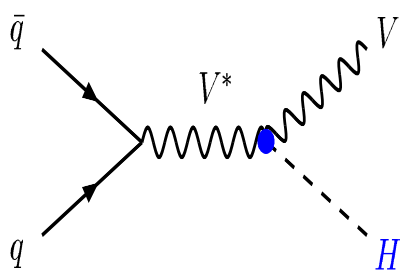
- **Total Higgs decay width:**
- $\mathcal{O}$(MeV) for $M_H \sim 100$ GeV (small)
- $\mathcal{O}$(TeV) for $M_H \sim 1$ TeV (obese).



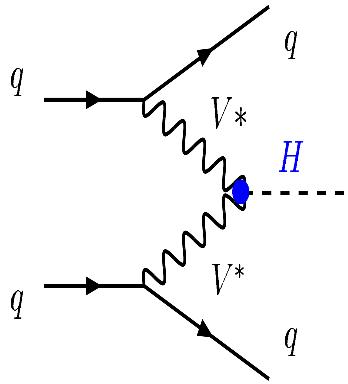
3. Higgs production at LHC

Production mechanisms

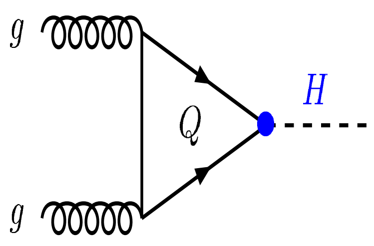
Higgs–strahlung



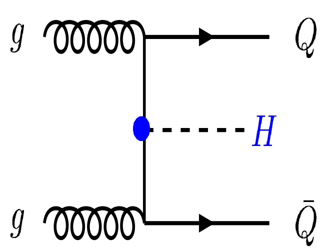
Vector boson fusion



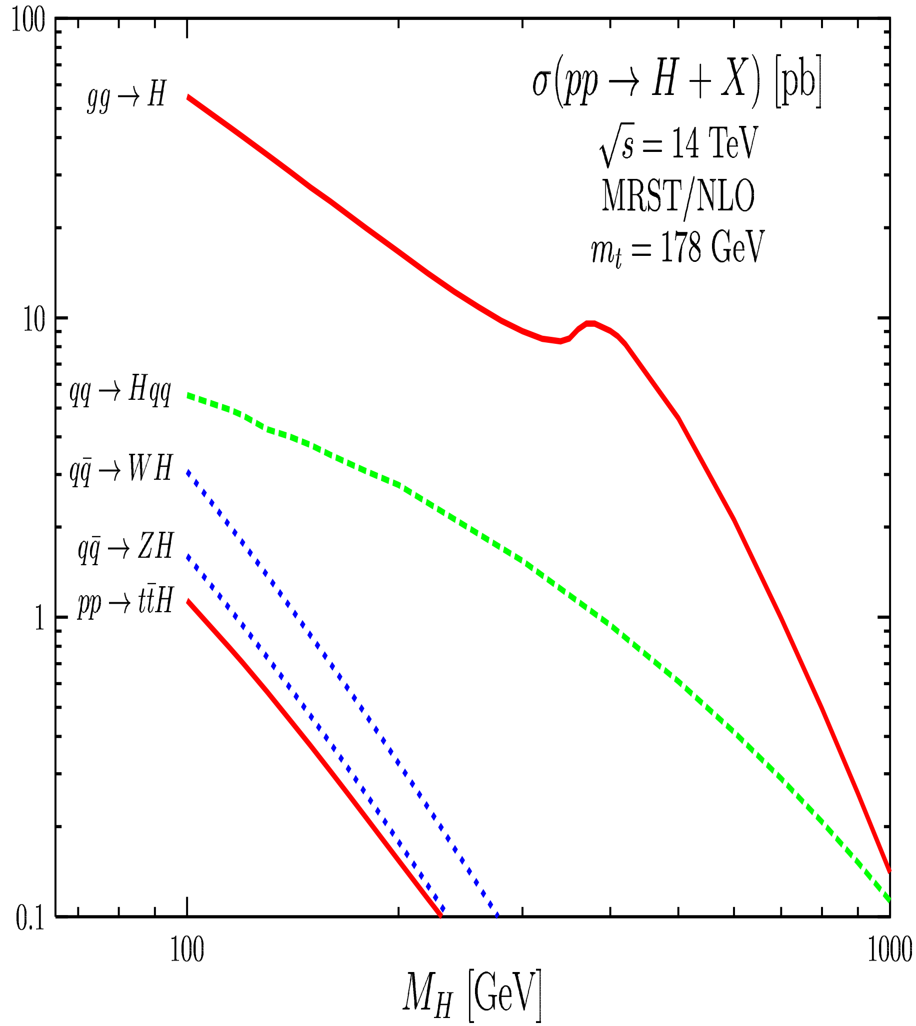
gluon–gluon fusion



in associated with $Q\bar{Q}$



Cross sections at the LHC

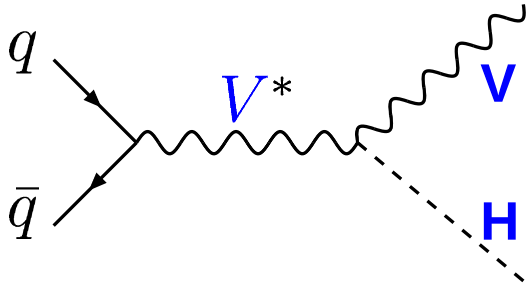


There are also subleading processes, $gg \to HH$, etc...

3. SM Higgs production: associated HV

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

The associated HV production:



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

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

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

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

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

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

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

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

3. 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.

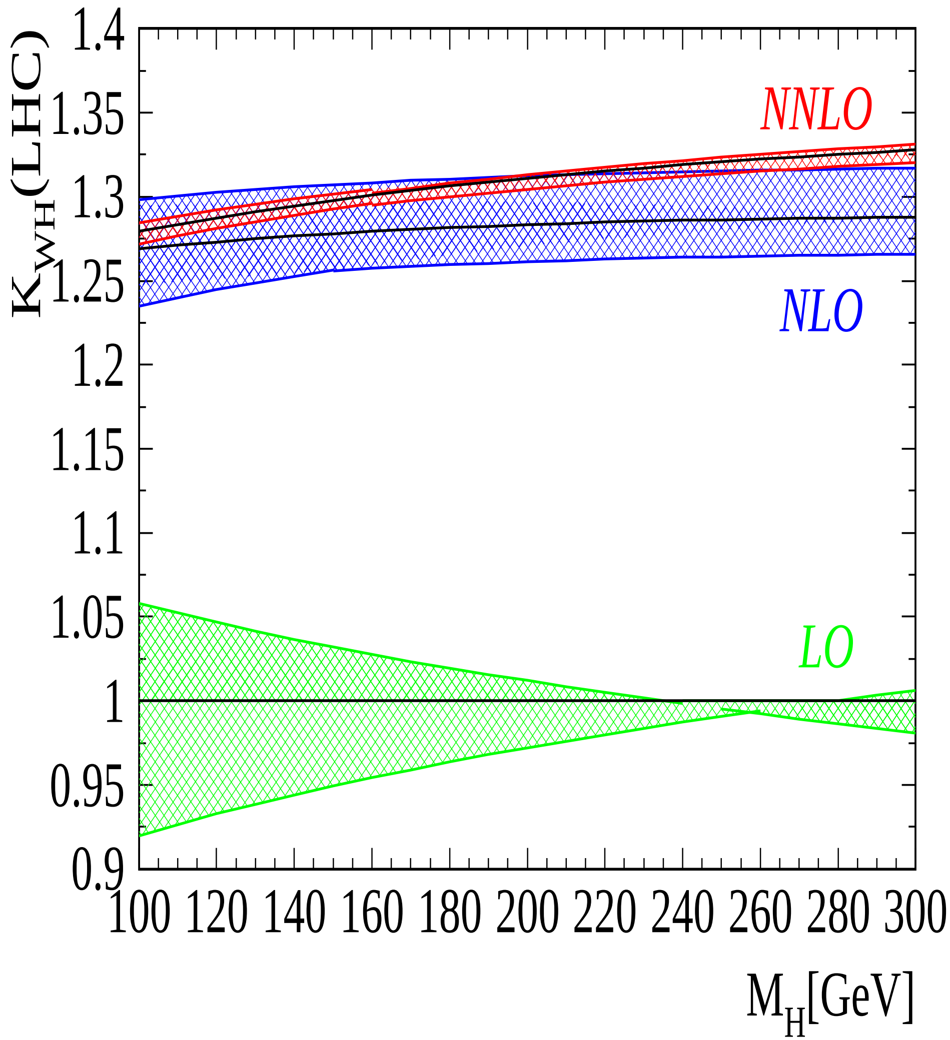
RC parameterized by K–factor:

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

Can also define K-factor at LO.

QCD RC known up to NNLO.

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



3. SM Higgs production: associated HV

Up-to-now, it only plays a marginal role at the LHC (small rates etc...).

Interesting final states are: $\mathbf{WH \to \gamma\gamma\ell, b\bar{b}\ell, 3\ell}$ **and** $\mathbf{ZH \to q\bar{q}\nu\nu}$**.**

Analyses by ATLAS+CMS: 5σ **discovery possible with** $\mathcal{L} \gtrsim 100$ **fb.**

But very clean channel when normalized to $\mathrm{pp \to Z}$**. Measurements!**

However:

WH channel is the most important at Tevatron:

$M_H \lesssim 130$ **GeV: H**$\to$ **bb:**

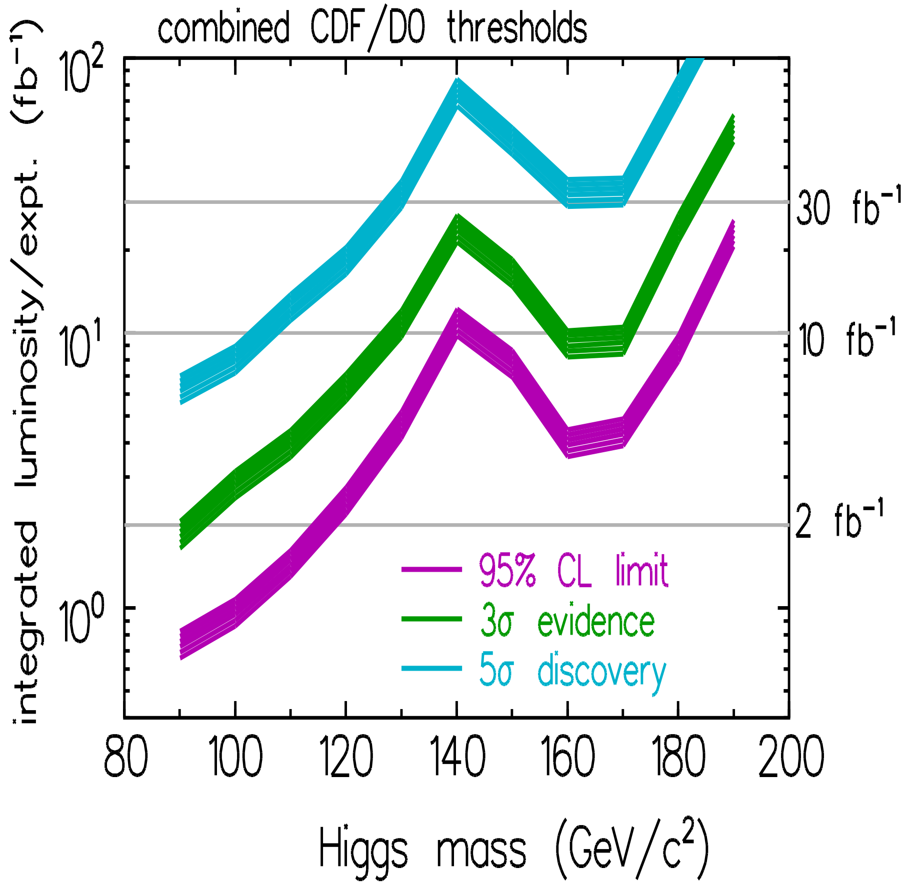
$\Rightarrow \ell\nu b\bar{b},\ \nu\bar{\nu}b\bar{b},\ \ell^+\ell^- b\bar{b}$

$M_H \gtrsim 130$ **GeV: H**$\to$ **WW***

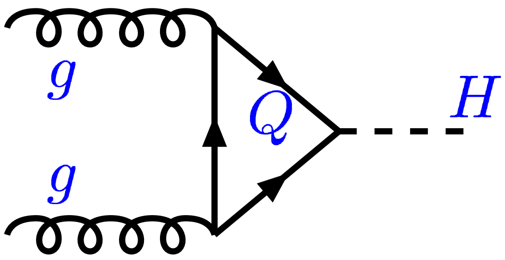
$\Rightarrow \ell^\pm\ell^\pm jj,\ 3\ell^\pm$

Possible discovery!!

(Report Tevatron HWG)



3. 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

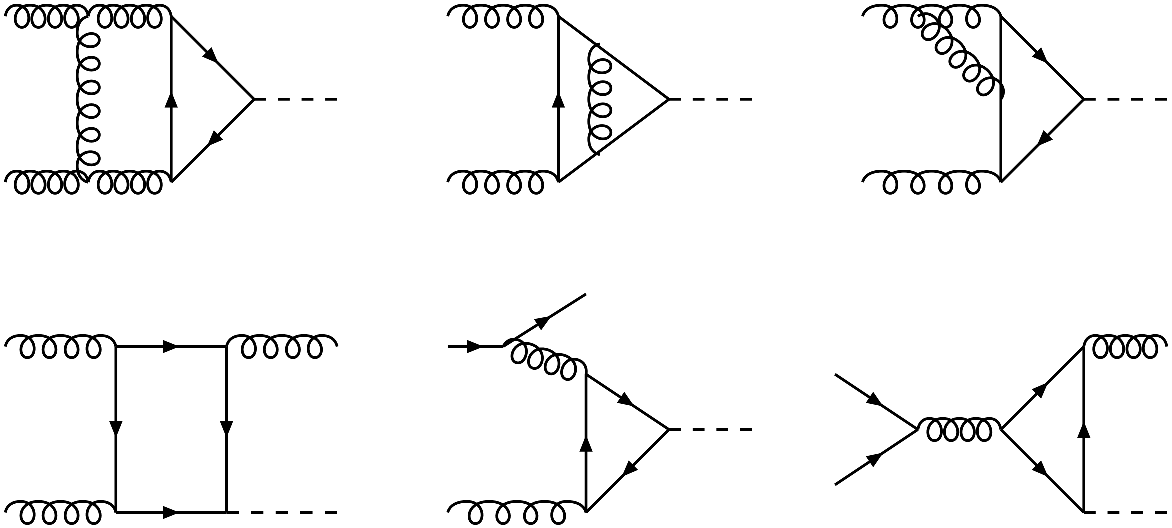
$gg \to H$ is the leading production process at the LHC.

- **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.**

3. 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.**

3. SM Higgs production: gg fusion

- Corrections known exactly, i.e. for finite m_t and M_H, at NLO:

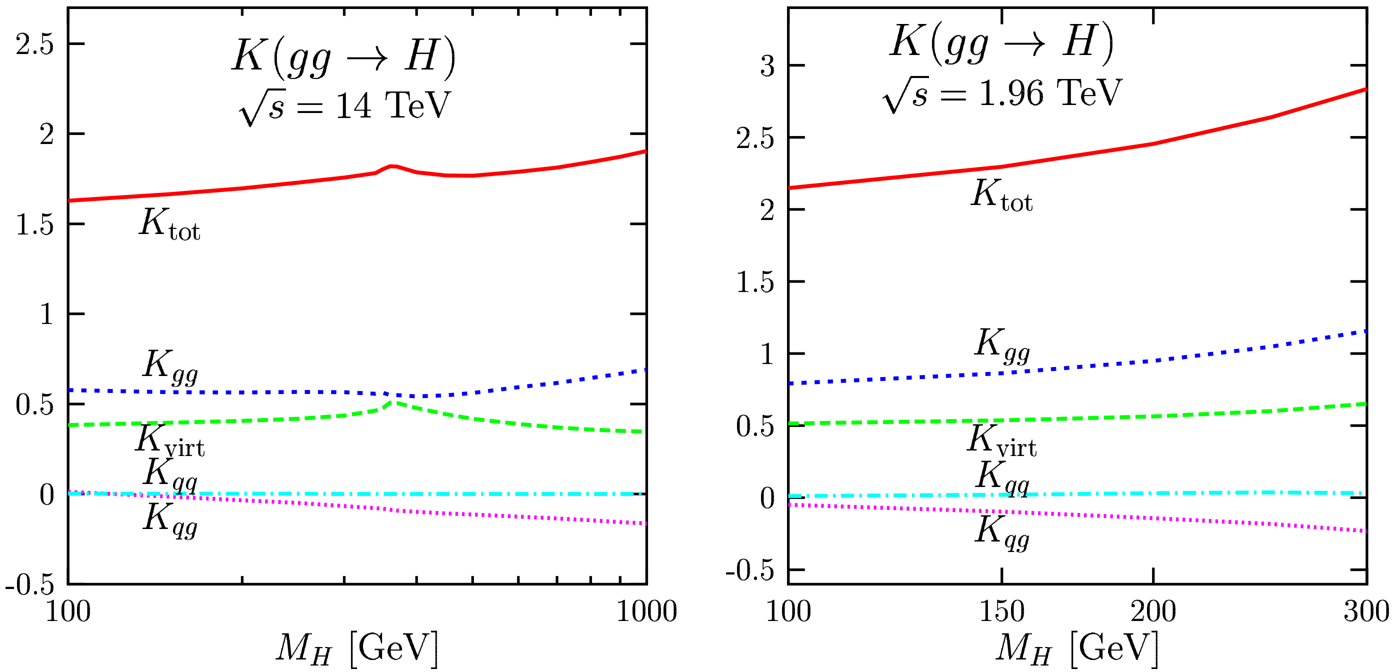
– quark mass effects are important for $M_H \gtrsim 2m_t$.

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

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



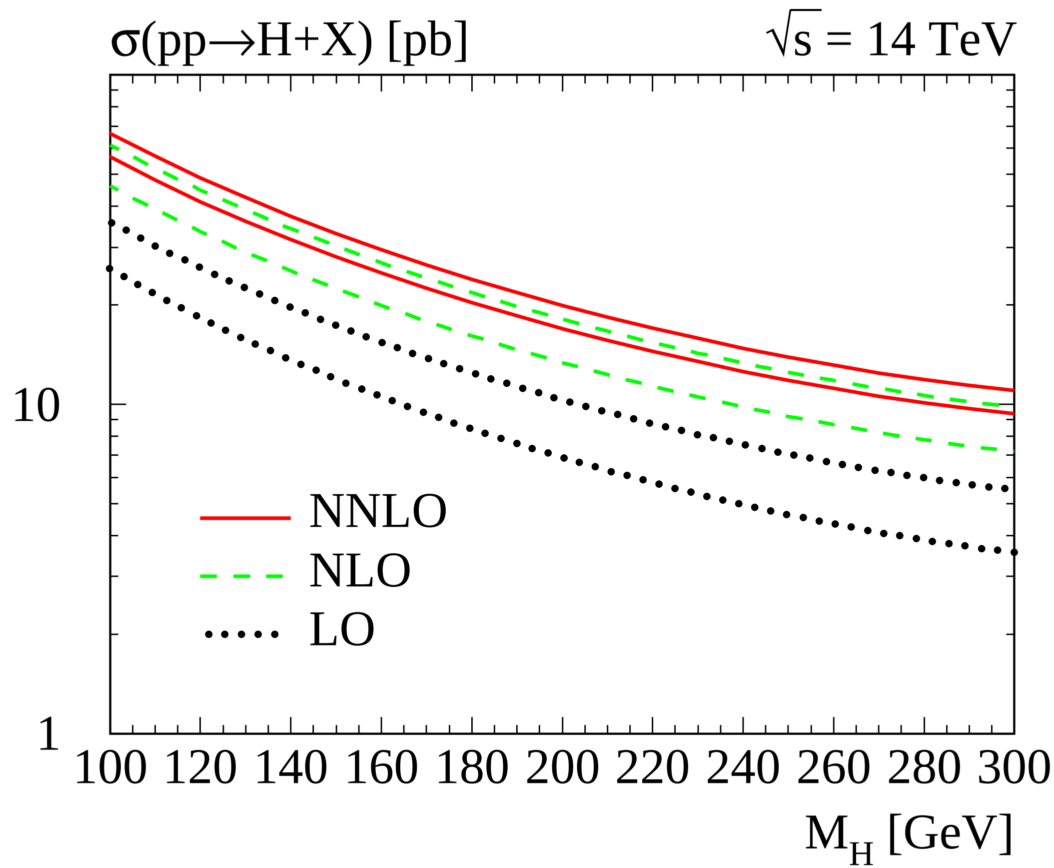
3. SM Higgs production: gg fusion

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



3. SM Higgs production: gg fusion

Relevant detection signals

- $\mathbf{H \to b\bar{b}, \tau^+\tau^-, t\bar{t}}$: **hopeless.**
- $\mathbf{H \to \gamma\gamma}$ **for** $\mathbf{M_H \lesssim 150}$ **GeV:**

– **large** σ **and small BR: many events left.**

– **huge irreducibe bkgs from jets:** 10^6 **rejection.**

– **large physics bkg from** $\mathbf{q\bar{q}/gg \to \gamma\gamma + X}$**.**

– **measure** $\mathrm{d}\sigma/\mathrm{dM}_{\gamma\gamma}$ **on both sides of peak.**

– $\mathbf{S/B = 1/30}$ **for** $\mathrm{M}_{\gamma\gamma} \sim \mathbf{2}$ **GeV (good** $\gamma\gamma$ **res.).**

- $\mathbf{H \to WW \to \ell\ell\nu\nu}$ **for** $\mathbf{M_H} \sim$**130–200 GeV:**

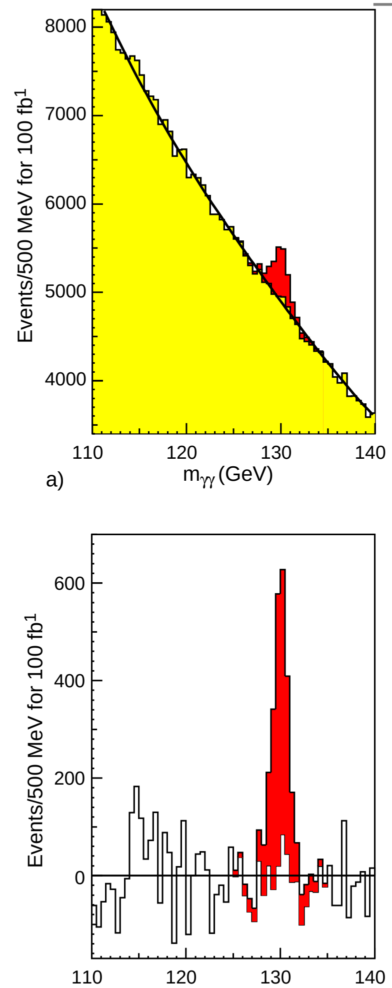
– **large** $\sigma \times \mathrm{BR}$ **in this range but no** $\mathrm{M_H^{recons}}$

– **large bkg from WW/tt but use spin-correlations!**

- $\mathbf{H \to ZZ \to 4\ell^\pm}$ **for** $\mathbf{M_H \gtrsim}$ **180–500 GeV:**

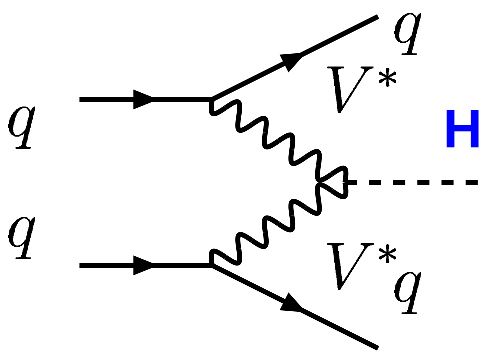
– **gold plated mode, clean and small/measurable ZZ bkg.**

- $\mathbf{H \to ZZ \to \ell\ell jj, \ell\ell\nu\nu, WW \to \ell\nu jj}$ **for** $\mathbf{M_H}$**=0.5–1 TeV.**



a)
b)

3. SM Higgs production: WW fusion



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

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

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

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

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

Large cross section: in particular for small M_H and large c.m. energy:

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

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:

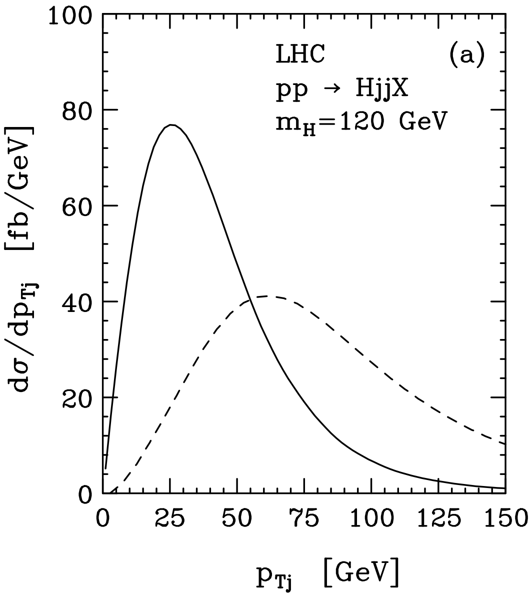
QCD corrections only consist of known corrections to the PDFs!

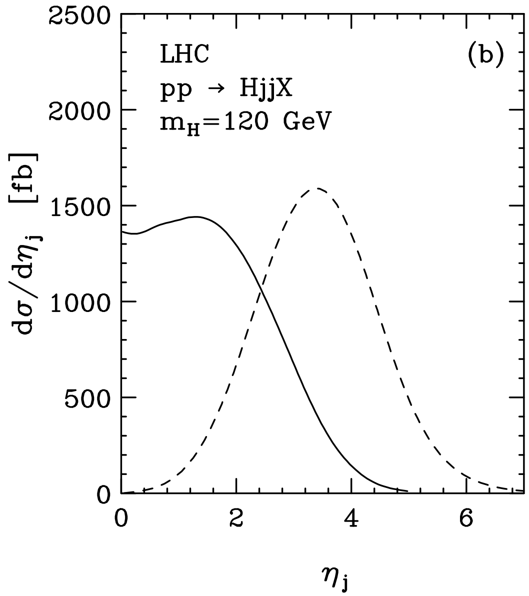
3. SM Higgs production: WW fusion

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

3. SM Higgs production: WW fusion

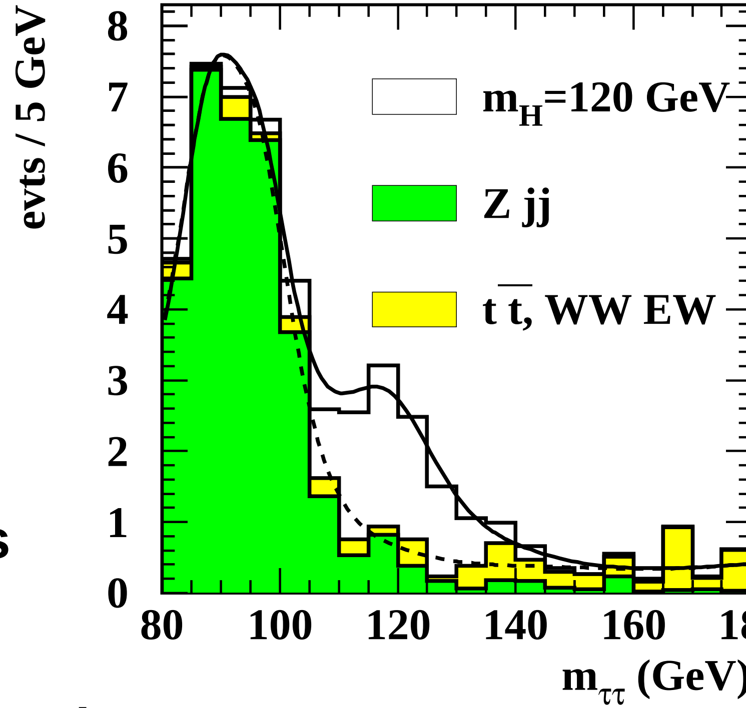
Relevant detection signals

- $\mathbf{H} \to \tau^+\tau^-$ for $\mathrm{M_H} \lesssim 150$ GeV:

first to be established: needs $\mathcal{L}\sim 30\mathrm{fb}^{-1}$

$\mathrm{M}_{\tau^+\tau^-}^{\mathrm{recons.}}$ against WW/tt/Zjj bkg.

τ polarization usefull against $\mathrm{Z} \to \tau^+\tau^-$



- $\mathbf{H} \to \gamma\gamma$ for $\mathrm{M_H} \lesssim 150$ GeV:

very clean with small/measurable bkgs

rare/needs $\mathcal{L}$+combine with other channels

- $\mathbf{H} \to \mathbf{WW} \to \ell\ell\nu\nu$

very difficult as you need to know background.

but feasible at low $\mathrm{M_H}$ and efficient at high $\mathrm{M_H}$.

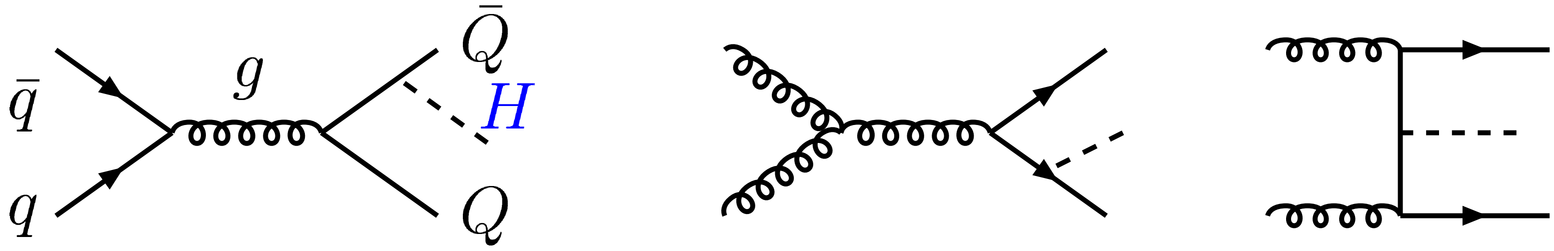
- $\mathbf{H} \to \mathbf{ZZ} \to \ell\ell\nu\nu, \ell\ell\mathrm{jj}$: have large bkg

need high $\mathcal{L}$, usefull at high masses in combination.

- $\mathbf{H} \to \mathrm{b\bar{b}}, \mathrm{t\bar{t}}$ very difficult and $\mathbf{H} \to \mu^+\mu^-$ needs high $\mathcal{L}$.

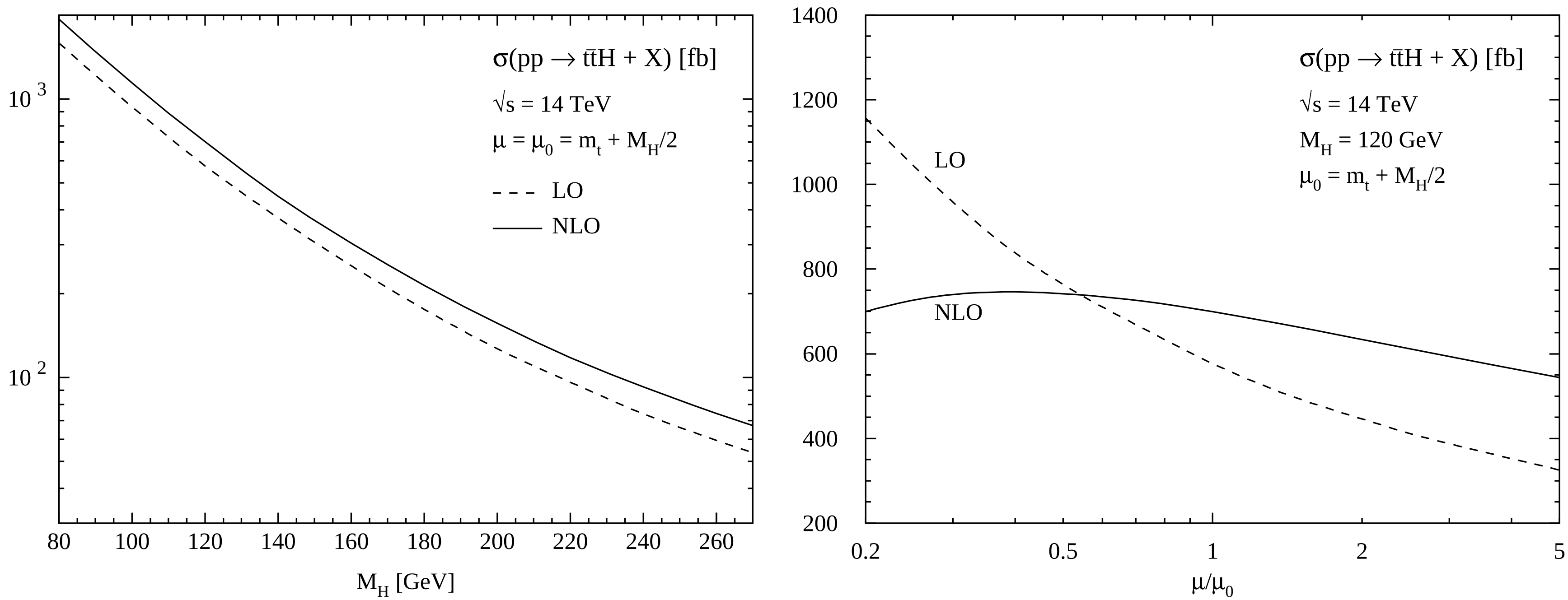
3. SM Higgs production: Htt production

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



NLO corrections recently calculated (Zerwas et al., Dawson et al.):

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



3. SM Higgs production: Htt production

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

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

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

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

Interesting signals at the LHC for this process are:

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

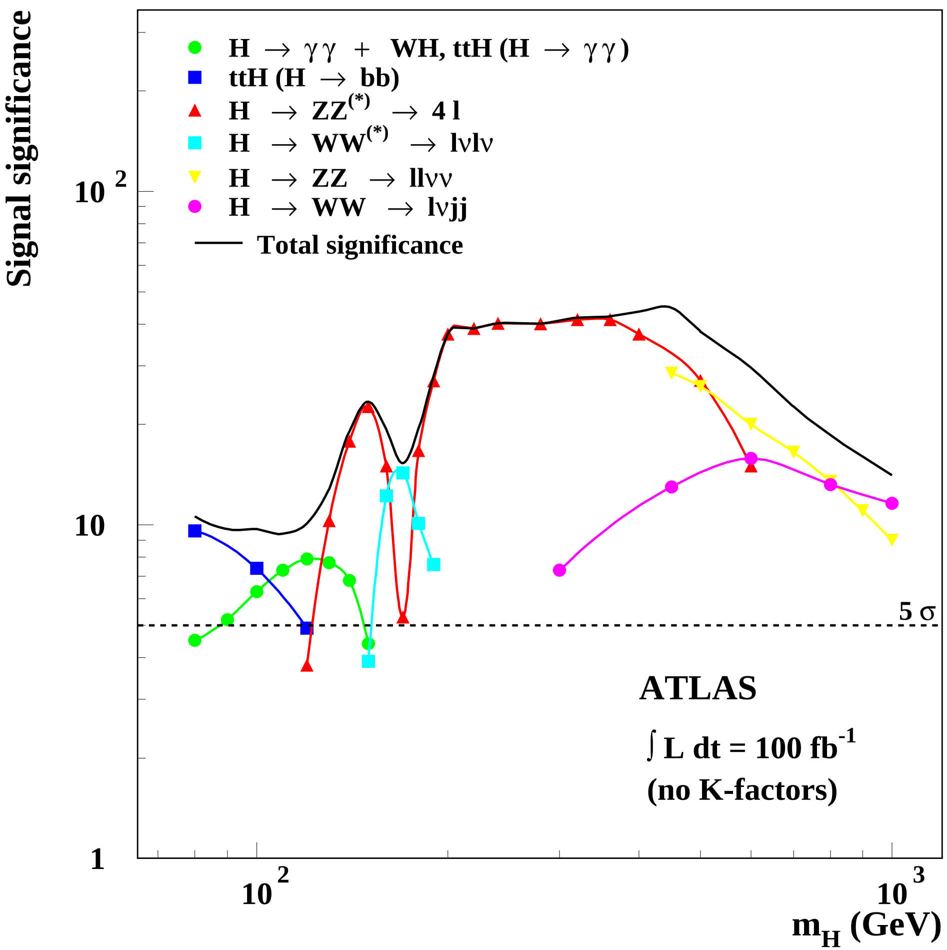
Possibility for a 3–5 signal at $\mathrm{M_H} \lesssim 140$ GeV with high luminosity.

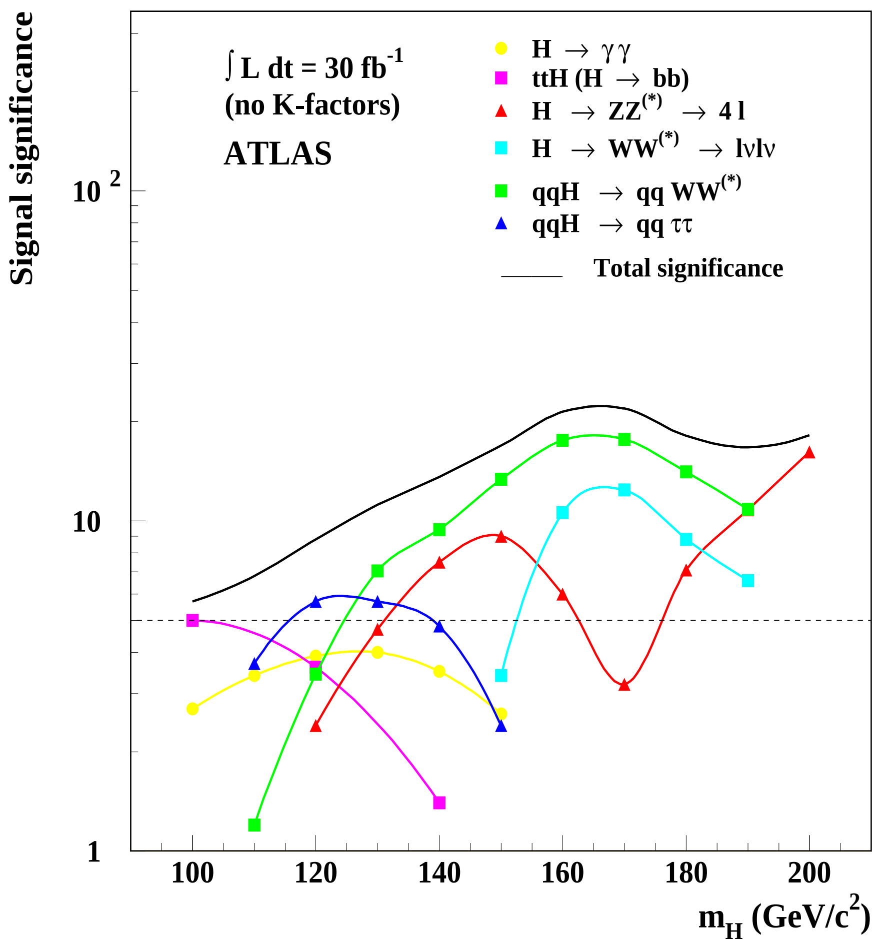
Needs to be combined with similar channels and topologies (eg: $\mathrm{pp \to WH} \to \ell\gamma\gamma, \ell\mathrm{b\bar{b}}$) to increase total signal significance.

But process very important for measurement of Htt Yukawa coupling!

3. SM Higgs production: summary

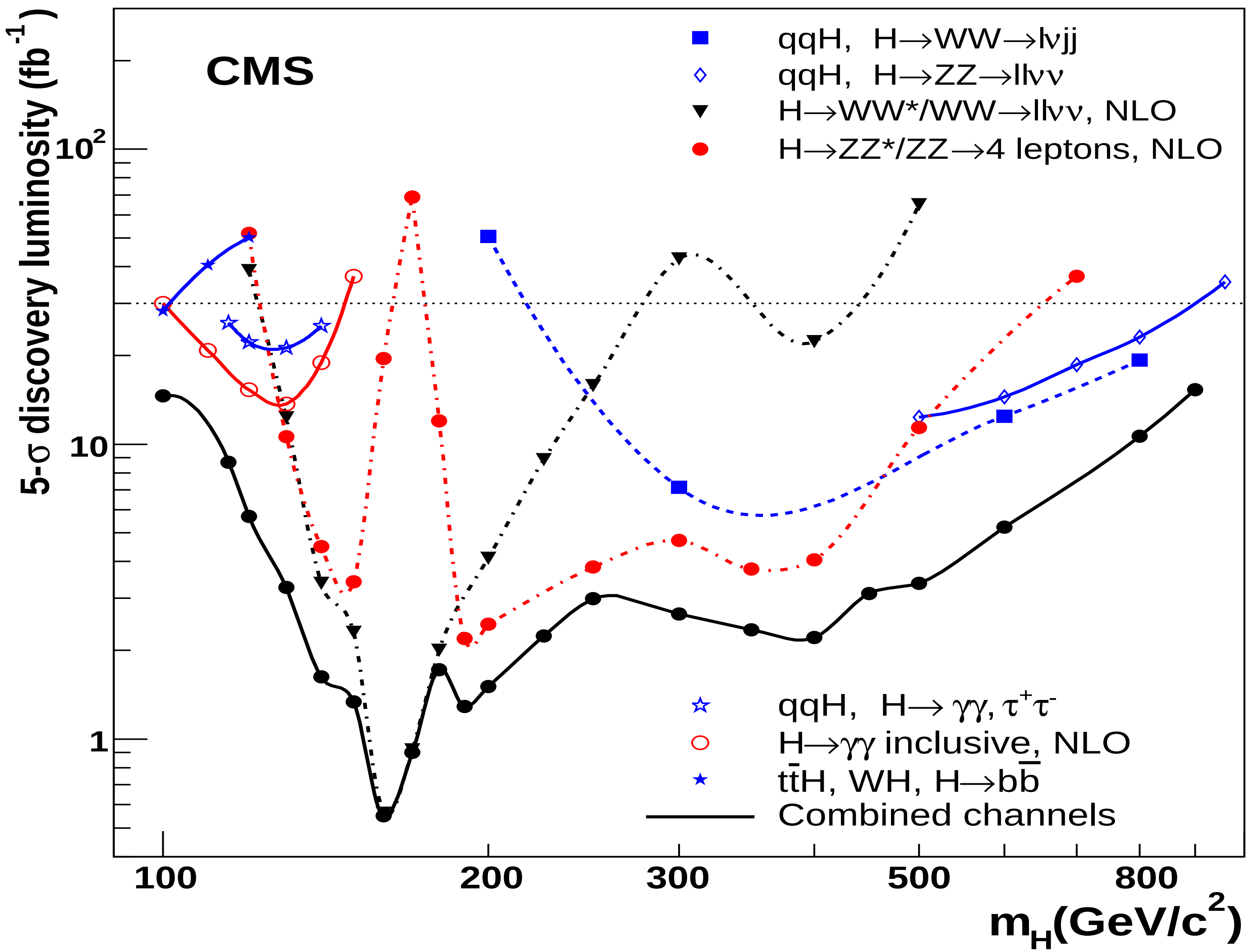
All in all, when you do the hard experimental work, you will get:





3. SM Higgs production: summary

Another way too summarize the expections: in terms of luminosity



4. Measurement of Higgs properties

So in 2-3 years from now we will find the Higgs (and maybe nothing else):

we celebrate, shake hands, drink champagne, 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...

4. 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

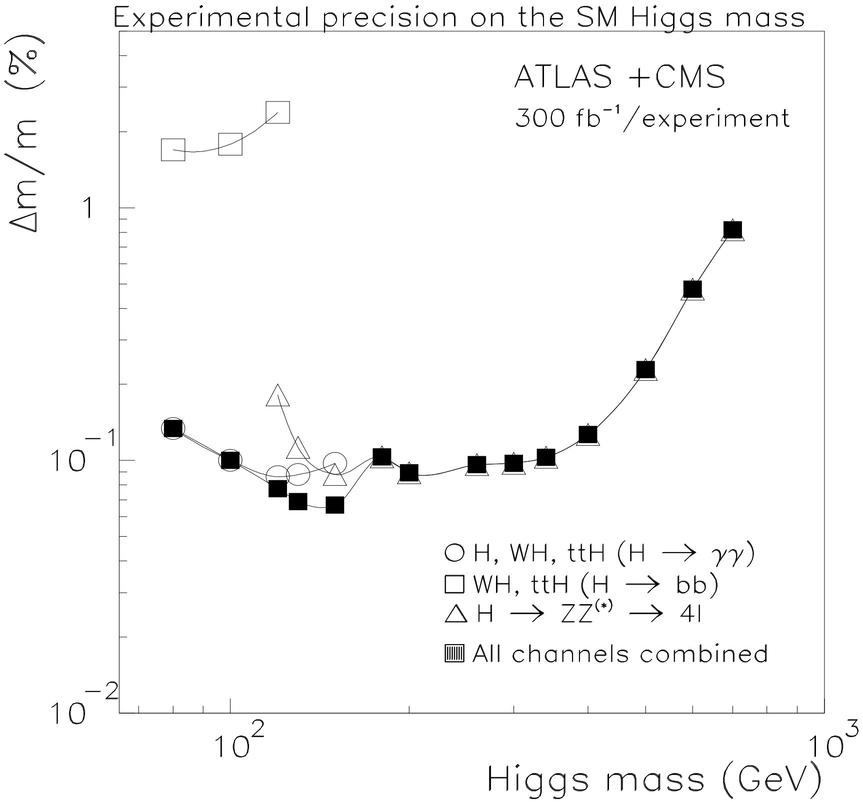
Final $\Delta \mathrm{M_H}/\mathrm{M_H} \sim 0.1\%$ to 1%.

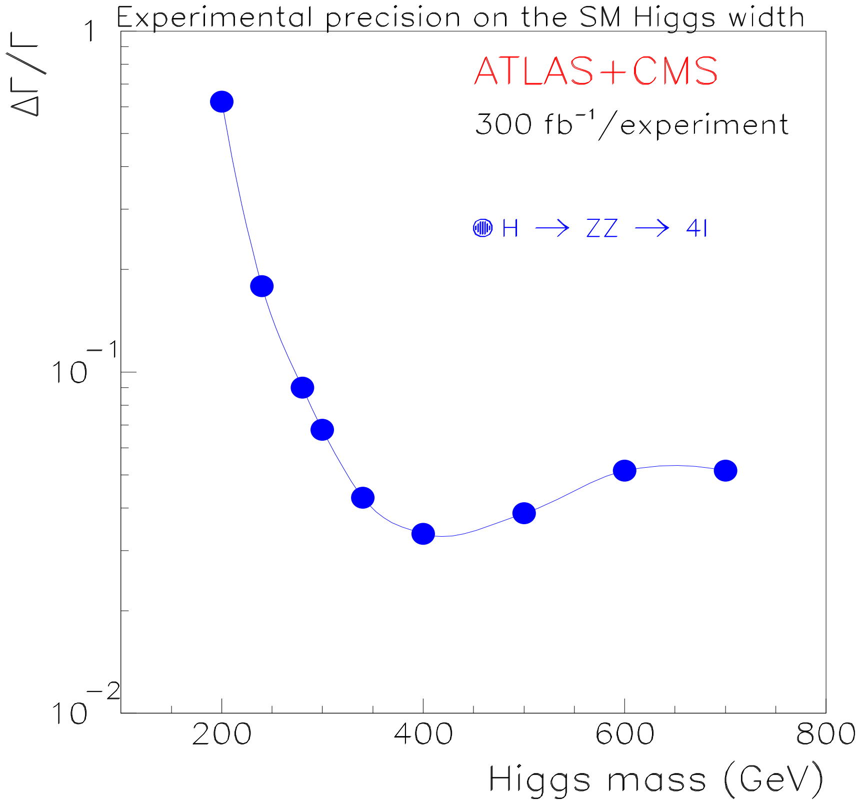
Higgs boson total width:

– 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 M_H effects from large width are important!

4. Higgs properties: J^{PC} numbers

- **Higgs spin:**

Higgs can be observed in $H \to \gamma\gamma$ decays: rules out J=1 and fixes C=+,

– argument not generalizable to $H \leftrightarrow gg$ since no g/q distinction,

– other particle spin–assignements might be possible J=2 (radion), etc.

- **Higgs parity:**

– Higgs can be observed in $H \to ZZ \to 4\ell^{\pm}$ rules out CP–odd state.

– Higgs spin–correlations in $gg \to H \to WW^*$ also useful here...

But we need to check that H is pure CP–even with no CP–odd mixture:

– it becomes then a challenging high–precision measurement,

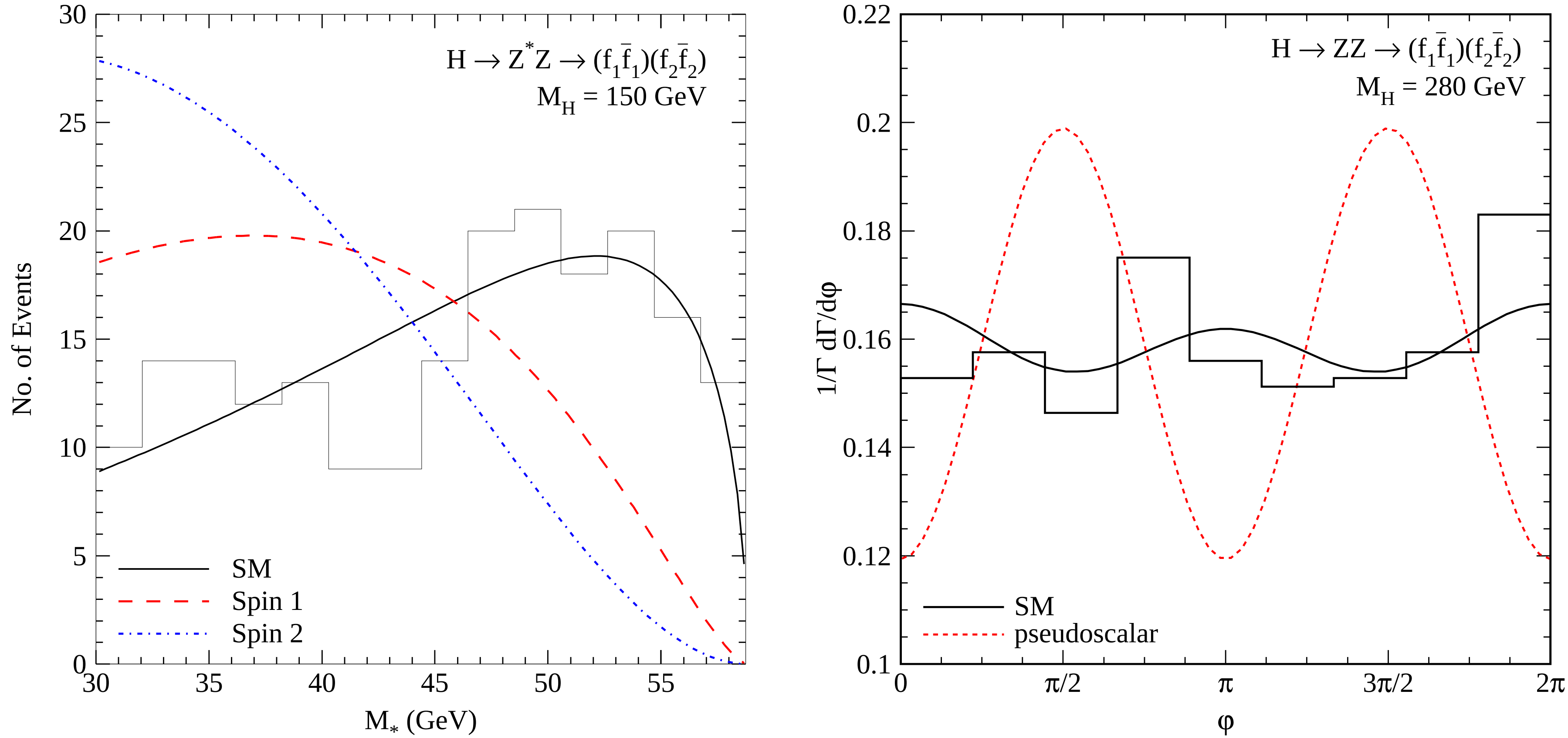
– can be done roughly by looking at correlations in $H \to ZZ, WW$.

Drawback: If H is mostly CP–even, rates for $A \to VV$ too small...

More convincing to look at more democratic Higgs-fermion couplings.

Possible channels: $H \to \tau^+\tau^-$ or $pp \to t\bar{t}H$: very challenging!!

4. Higgs properties: J^{PC} numbers



left: threshold behavior of $\mathrm{d}\Gamma(\mathrm{H} \to \mathrm{ZZ}^*)/\mathrm{dM}_*$ distribution for J=0,1,2

right: azimuthal distributions $\mathrm{d}\Gamma(\mathrm{H} \to \mathrm{ZZ})/\mathrm{d}\phi$ for SM and CP-odd A

ATLAS simulation including bkgs with $\int \mathcal{L}\mathrm{dt} = 300\,\mathrm{fb}^{-1}$ at the LHC

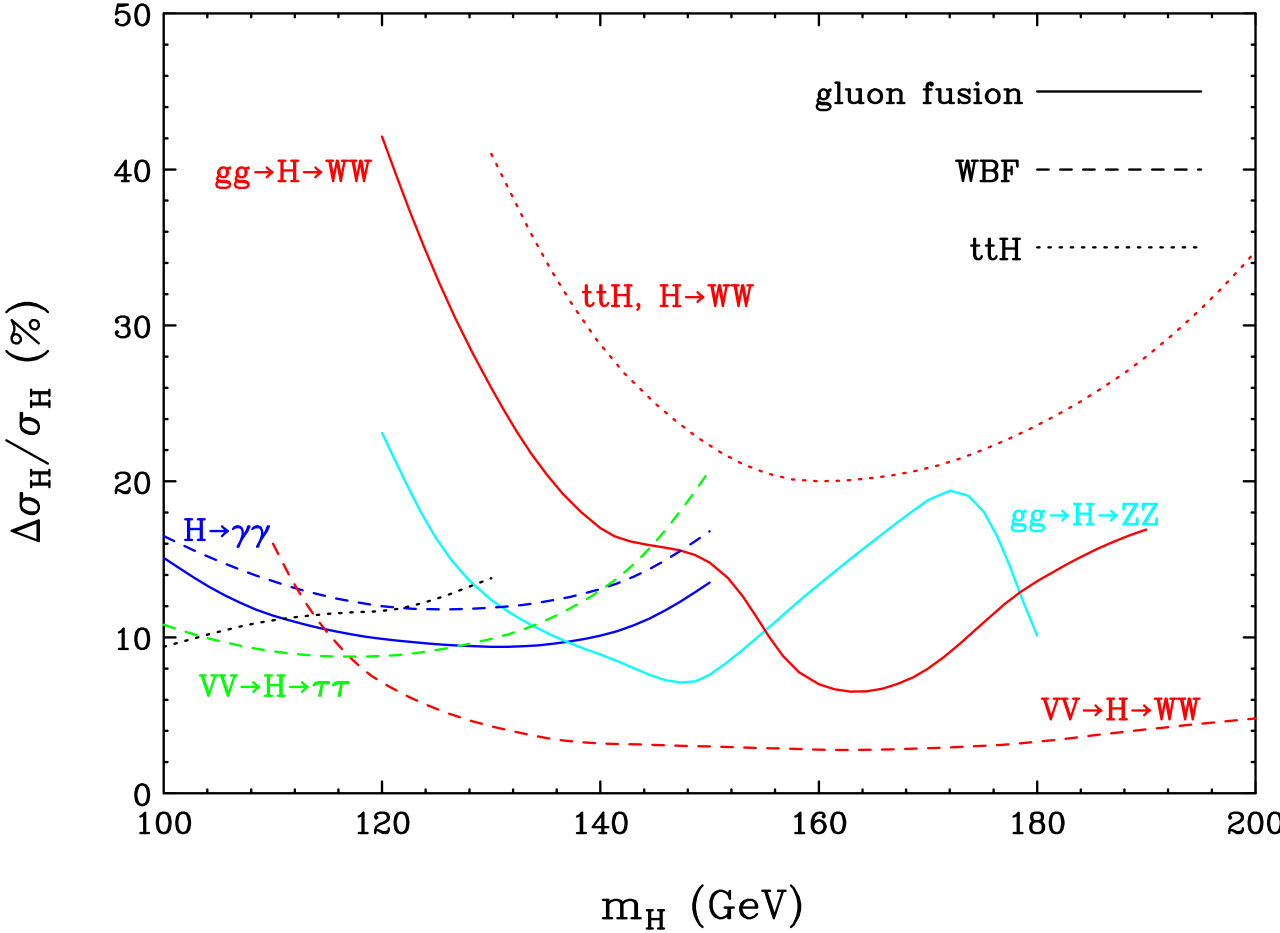
4. Higgs properties: Higgs couplings

Higgs couplings can be determined by looking at various Higgs production and decay channels and measuring $\mathrm{N_{ev}} = \sigma \times \mathrm{BR}$.

LHC with $\mathcal{L} = 300$fb^{-1}.

Only statistical errors.

D. Zeppenfeld et al.



4. Higgs properties: Higgs couplings

The errors are in general rather large unfortunately:

- **experimental errors: statistics, systematics, parton luminosity,...**
- **theoretical errors: PDFs, HO+scale variation, model dependence...**

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

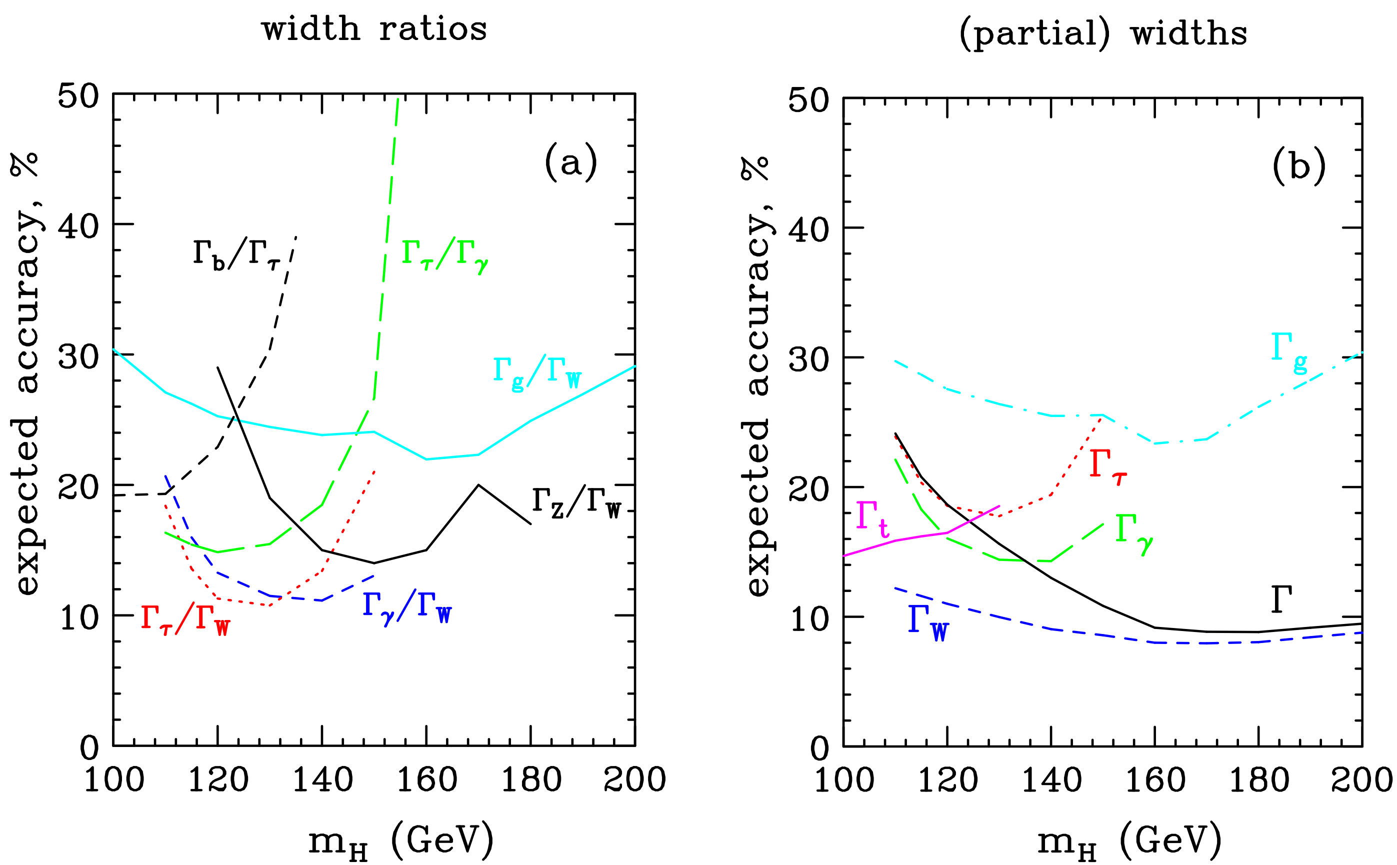
Process	Measurement quantity	Error	Mass range
$\frac{(t\bar{t}H+WH)\to\gamma\gamma+X}{(t\bar{t}H+WH)\to b\bar{b}+X}$	$\frac{\mathrm{BR}(H\to\gamma\gamma)}{\mathrm{BR}(H\to b\bar{b})}$	$\sim 15\%$	$80 - 120$ GeV
$\frac{H\to\gamma\gamma}{H\to 4\ell^{+}}$	$\frac{\mathrm{BR}(H\to\gamma\gamma)}{\mathrm{BR}(H\to ZZ^{*})}$	$\sim 7\%$	$120 - 150$ GeV
$\frac{t\bar{t}H\to\gamma\gamma,b\bar{b}}{WH\to\gamma\gamma,b\bar{b}}$	$(g_{Htt}/g_{HWW})^2$	$\sim 15\%$	$80 - 120$ GeV
$\frac{H\to ZZ^{*}\to 4\ell^{+}}{H\to WW^{*}\to 2\ell^{\pm}2\nu}$	$(g_{HZZ}/g_{HWW})^2$	$\sim 10\%$	$130 - 190$ GeV

Note: for $\mathrm{M_H} \gtrsim 2\mathrm{M_Z}$ only few processes accessible: $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ}$.

while $\sigma(\mathrm{gg} \to \mathrm{H})$ provides $\mathrm{g_{Htt}}$ but indirectly since loop mediated.

4. Higgs properties: Higgs couplings

- **Then translate into partial widths $\propto$ Higgs coupling squared.**
- **Precision on coupling measurement is:** $\Delta g_{HXX} = \frac{1}{2} \frac{(\Delta^{\exp}\Gamma + \Delta^{\rm th}\Gamma)}{\Gamma}$
- **Some theoretical assumptions (no invisible, SU(2) invariance, some couplings are known, etc..) allow to extract additional couplings....**

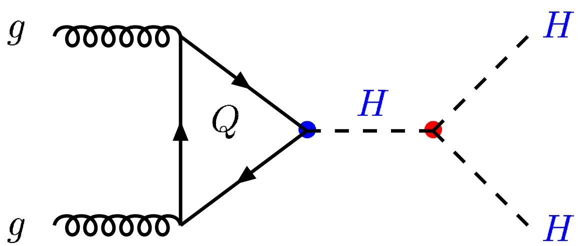


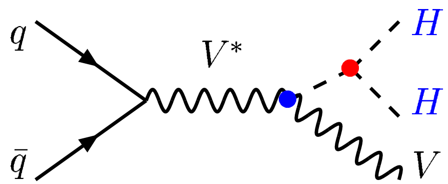
4. Higgs properties: Higgs self-couplings

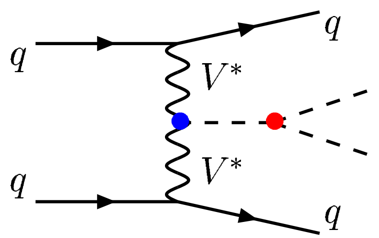
Important couplings to be measured: $g_{H^3}, g_{H^4} \Rightarrow$ **access to** V_H.

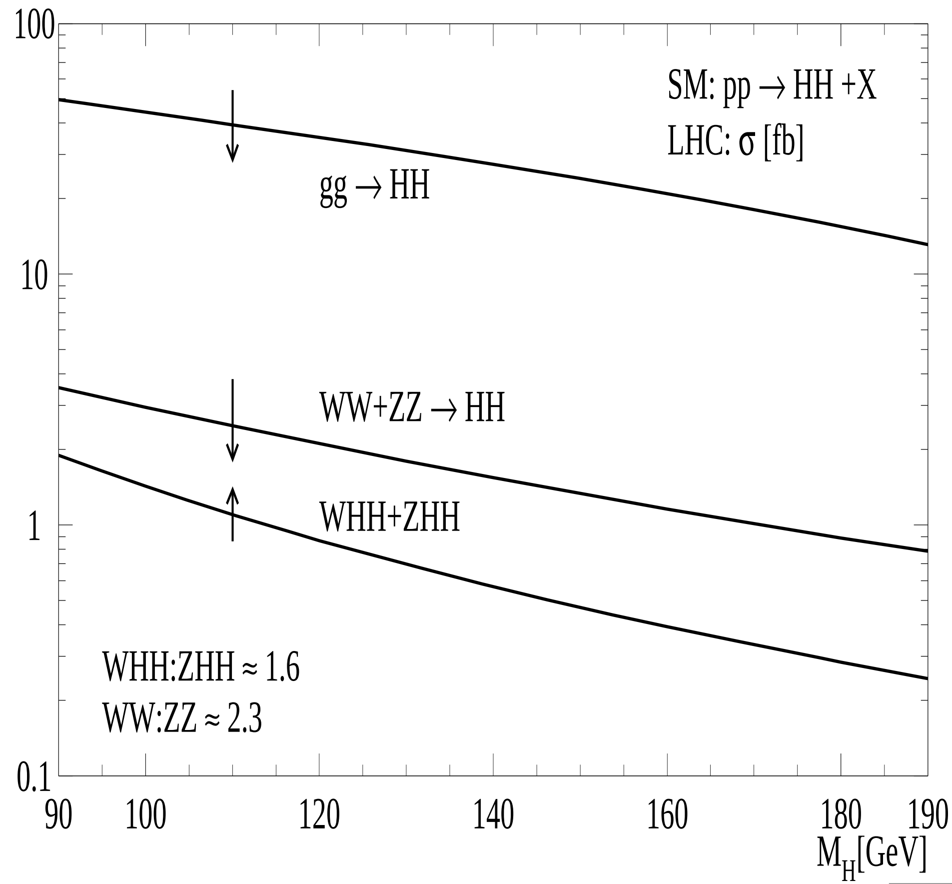
- g_{H^3} **is accessible in double Higgs production:** $pp \to HH + X$
- g_{H^4} **is hopeless to measure, needs pp→HHH+X with too low rates.**

Relevant processes for HH prod:









4. Higgs properties: Higgs self-couplings

Cross sections small, except maybe for gg→HH at $M_H \lesssim 200$ GeV:

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

Yes, it has been tried:

– parton level analysis...

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

– look at IM distributions

– use large luminosity.

Some hope to set limits....

Needs to go to SLHC...

U. Baur et al.