Higgs Physics: SM and MSSM

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- **EWSB in the SM**
- **Constraints on M_H**
- **Higgs decays**
- **The Higgs at the LHC**
- **The Higgs at the Tevatron**
- **Measurement of Higgs properties**
- **EWSB in SUSY**
- **The MSSM Higgs spectrum**
- **SUSY Higgsses at the LHC**

1. EWSB in the SM

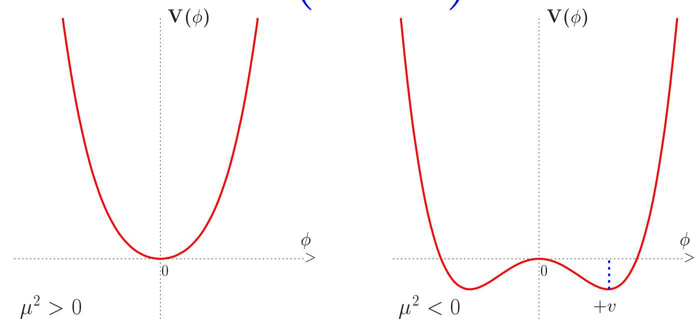
In the SM, if gauge boson and fermion masses are put by hand in $\mathcal{L}_{\rm SM}$

breaking of gauge symmetry $\Rightarrow$ 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 $\mathbf{SU(2)_L \times U(1)_Y}$

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

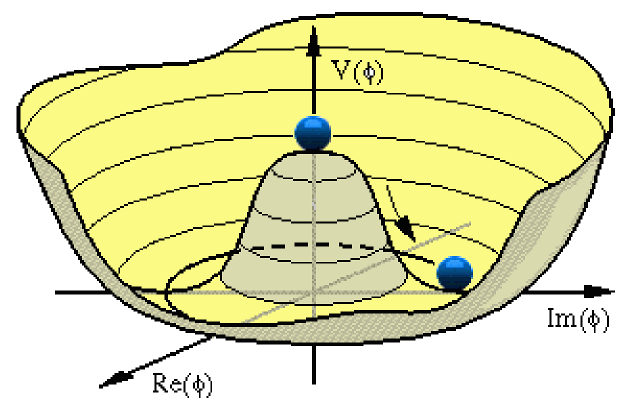


$\mu^2 > 0$: **4 scalar particles.**

$\mu^2 < 0$: 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 $\mathcal{L}_{\rm S}$ 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 $\mathcal{L}_{\mathrm{Yuk}}$ which is invariant under SU(2)xU(1):

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

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

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:**

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

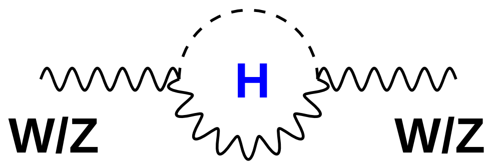
$$\Rightarrow g_{Hff} = im_f/v\,,\ g_{HVV} = -2iM_V^2/v\,,\ g_{HHVV} = -2iM_V^2/v^2$$

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

2. Constraints on M_H

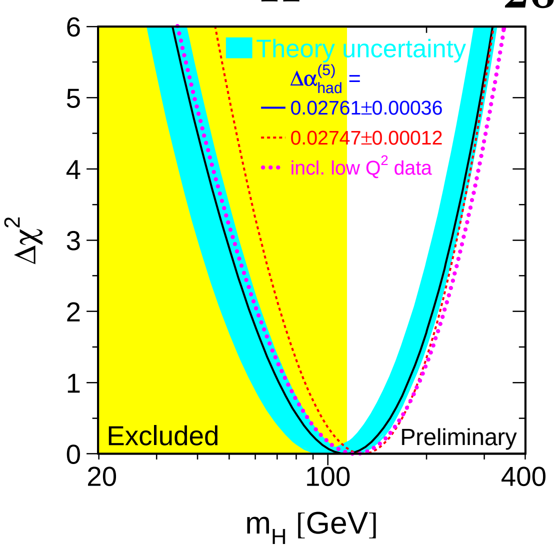
Indirect Higgs searches:

H contributes to RC to W/Z masses:



Fit the EW precision data $\to$ Hollik:

one obtains $M_H = 87^{+35}_{-26}$ GeV, or

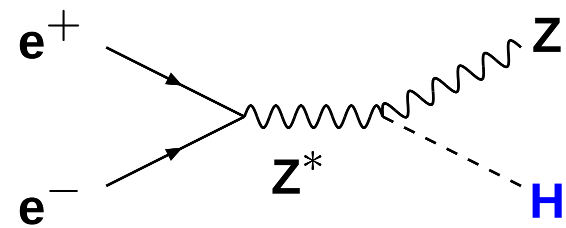


$M_H \lesssim 157$ GeV at 95% CL

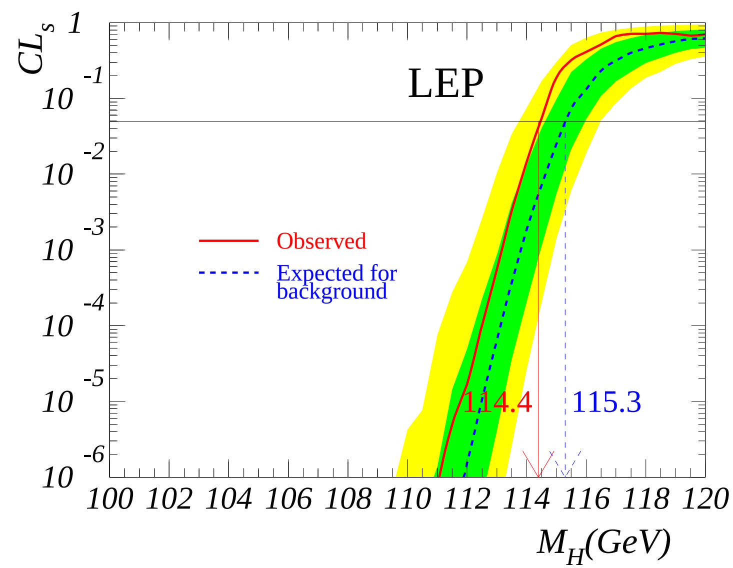
Beware: which m_t value? $\to$ Hoang

Direct searches at colliders:

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



$M_H > 114.4$ GeV @95%CL

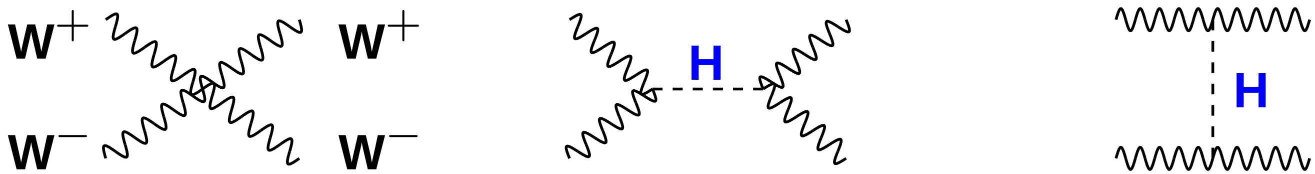


Tevatron $M_H \neq 158-175$ GeV

(to be discussed in details later on)

2. Constraints on M_H perturbative unitarity

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



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

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

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

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

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

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

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

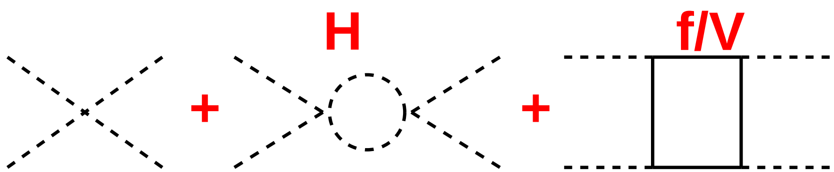
- **For a very heavy or no Higgs boson, we have: $a_0 \xrightarrow{s \ll M_H^2} -\frac{s}{32\pi v^2}$**

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

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

2. Constraints on M_H: triviality+stability

$\lambda \propto M_H^2$ increases with energy



Heavy H: H contributions dominant

RGE: $\frac{d\lambda(Q^2)}{dQ^2} = \frac{3}{4\pi^2}\lambda^2(Q^2) \Rightarrow$

$$\lambda(Q^2) = \lambda(v^2)/[1 - \frac{3}{4\pi^2}\log\frac{Q^2}{v^2}]$$

- $Q^2 \ll v^2$; $\lambda \to 0_+$: triviality
- $Q^2 \gg v^2$: $\lambda \to \infty$: Landau pole

SM only valid before $\lambda \lesssim 4\pi \ll \infty$

$$\Lambda_C = M_H \Rightarrow M_H \lesssim 650 \text{ GeV}$$

(Comparable to results on lattice!)

$$\Lambda_C = M_P \Rightarrow M_H \lesssim 180 \text{ GeV}$$

Light H: t/W/Z contributions dominant

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

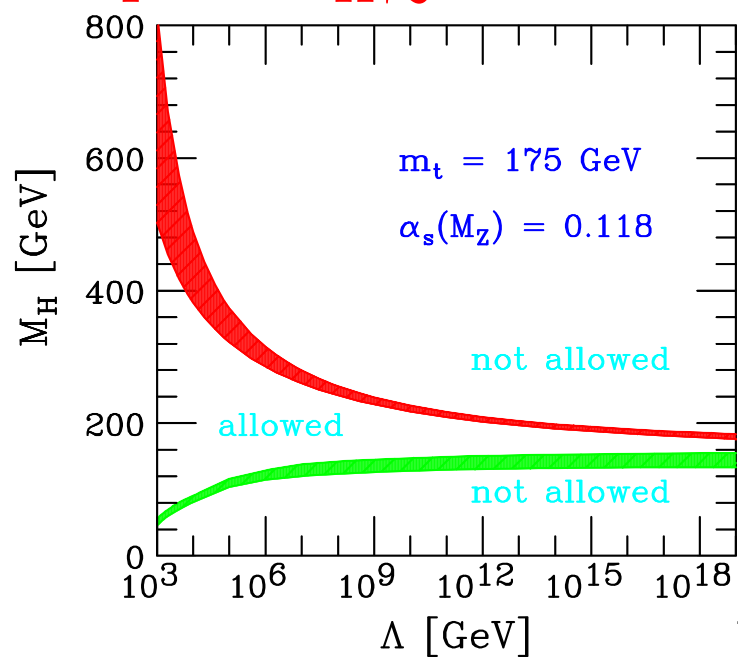
top loops might lead to $\lambda(0) < \lambda(v)$:

v not minimum / EW vacuum unstable

The SM is valid only if $\lambda(Q^2) > 0$

$$\Lambda_C \sim 1 \text{ TeV} \Rightarrow M_H \gtrsim 70 \text{ GeV}$$

$$\Lambda_C \sim M_P \Rightarrow M_H \gtrsim 130 \text{ GeV}$$

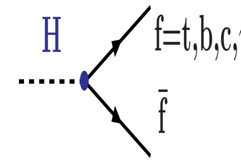


3. Higgs decays

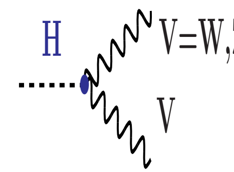
Higgs couplings proportional to particle masses: once $\mathrm{M_H}$ is fixed,

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

$$\mathbf{H \to f\bar{f}} : \Gamma = \frac{G_\mu N_c}{4\sqrt{2}\pi} \mathbf{M_H m_f^2} \beta_f^3$$

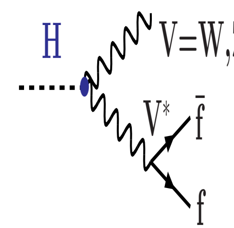


- **Only** $\mathrm{b\bar{b}, c\bar{c}}, \tau^+\tau^-, \mu^+\mu^-$ **and eventually** $\mathrm{t\bar{t}}$
- **QCD RC very large** $\Rightarrow \mathrm{m_b^{\overline{MS}}(M_H^2)} \sim 3\,\mathrm{GeV}$.
- **Also direct QCD (3-loops) and EW (1-loop).**

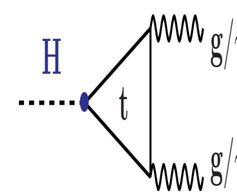


$$\mathbf{H \to VV}: \Gamma = \frac{G_\mu \mathbf{M_H^3}}{16\sqrt{2}\pi} \delta_V \beta_V \left(1 - 4\frac{M_V^2}{M_H^2} + 12\frac{M_V^4}{M_H^4}\right)$$

- **above** $2\mathrm{M_Z}$ **th. dominant: BR(WW)=**$\frac{2}{3}$**, BR(ZZ)=**$\frac{1}{3}$
- $\mathrm{M_H} \gg \mathrm{M_V}$**: very large** $\Gamma_{VV} \propto \mathrm{M_H^3}$ $(\Gamma_{tt} \propto \mathrm{M_H})$
- **below th. decays possible/important** $(\mathrm{m_b} \ll \mathrm{M_V})$**!**



$\mathbf{H \to gg/\gamma\gamma, Z\gamma}$**: loop induced** $\propto \mathcal{O}(\alpha_s^2/\alpha^2)$



- **Heavy particles do not decouple! mainly t(W) loops**
- $\mathrm{H \to gg}$**: large (#2) RC; reverse of** $\mathrm{gg \to H}$**!**
- $\mathrm{H} \to \gamma\gamma$**: much smaller (**$\propto \alpha^2/\alpha_s^2$**) but clean!**

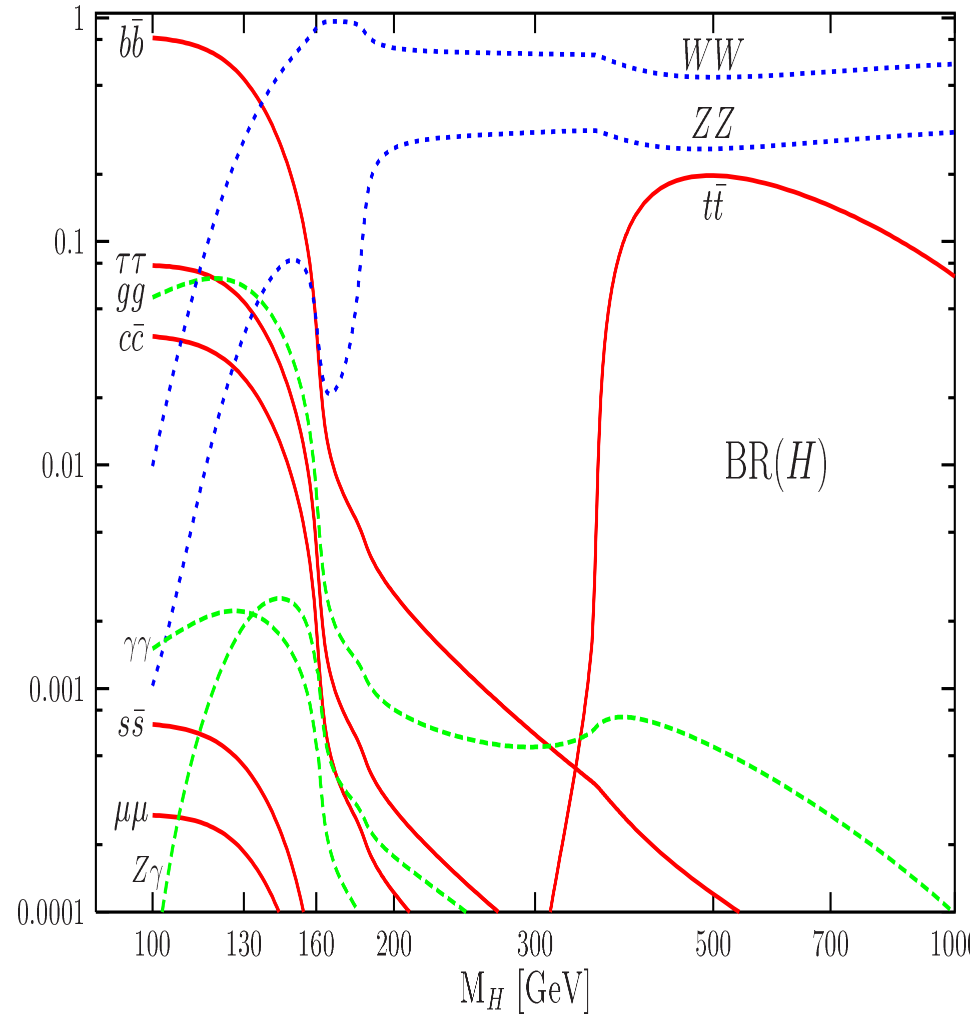
3. Higgs decays: branching ratios

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).**



HDECAY

3. Higgs decays: total width

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

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

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

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

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

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

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

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

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

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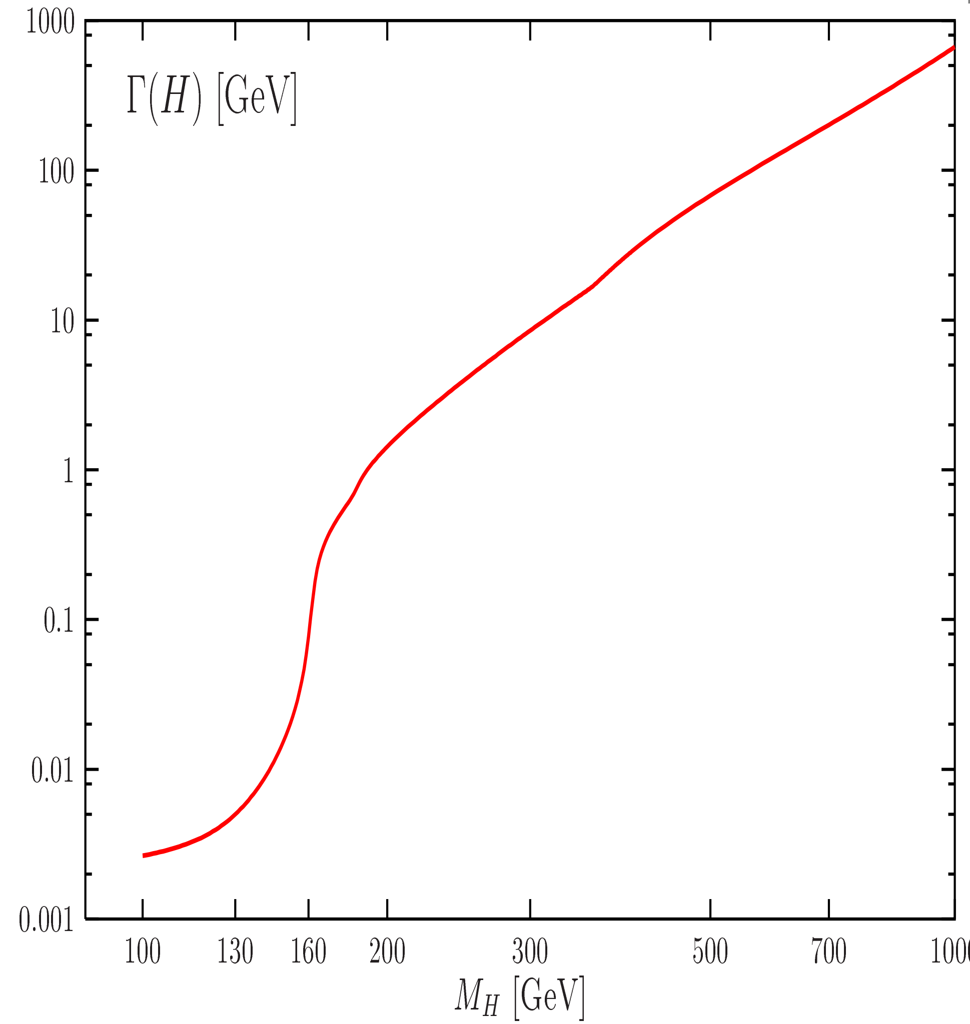
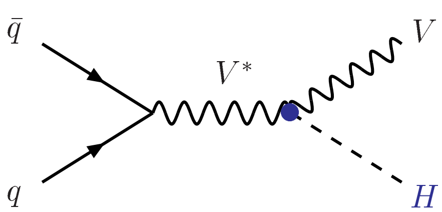


HDECAY

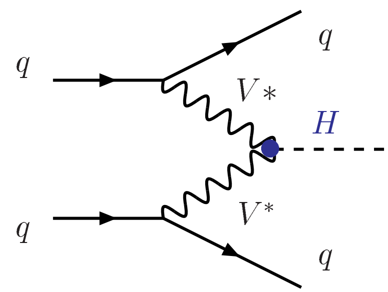
4. The Higgs at the LHC

Production mechanisms

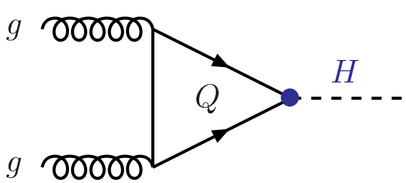
Higgs–strahlung



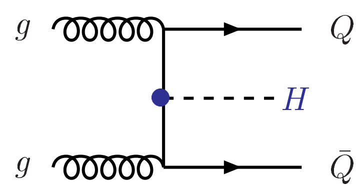
Vector boson fusion



gluon–gluon fusion



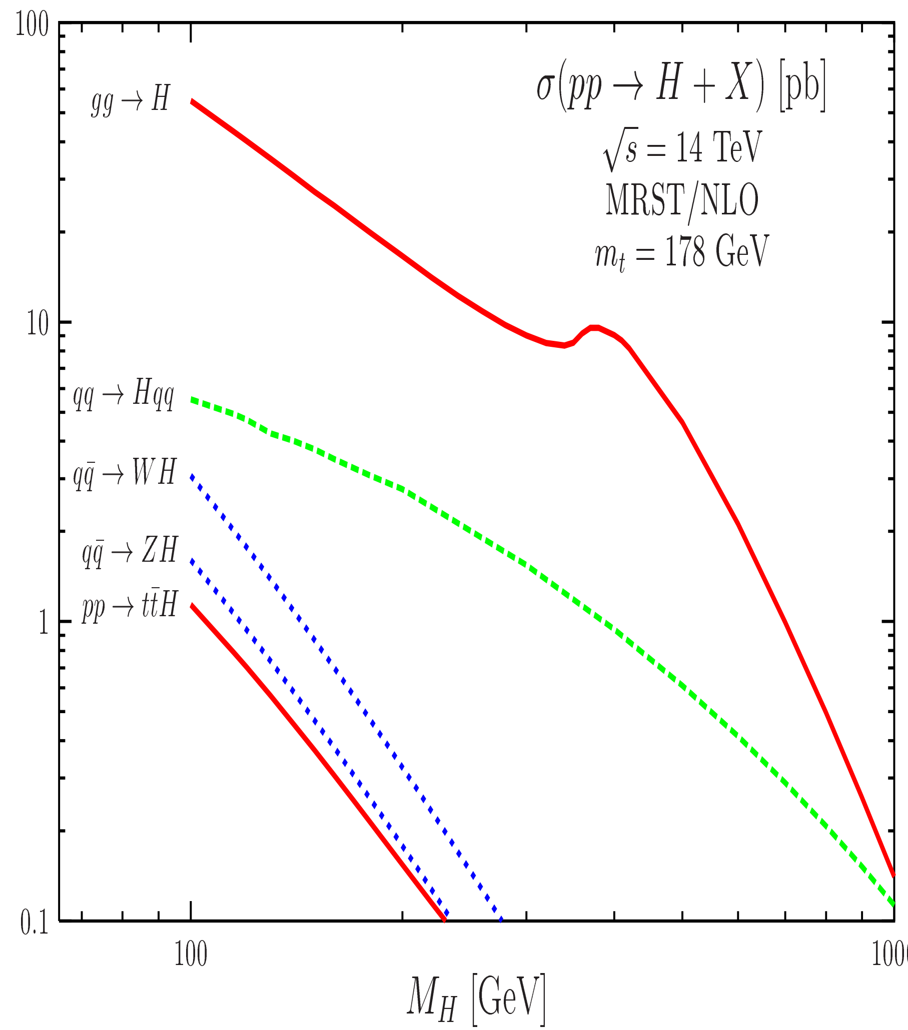
in associated with $Q\bar{Q}$



Also subleading processes,

$gg \to HH$, etc...

Cross sections at the LHC



4. The Higgs at the LHC: overview

H discovery: a very challenging task!

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

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

Trigger: get rid of uninteresting events...

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

Use different kinematic features for Higgs

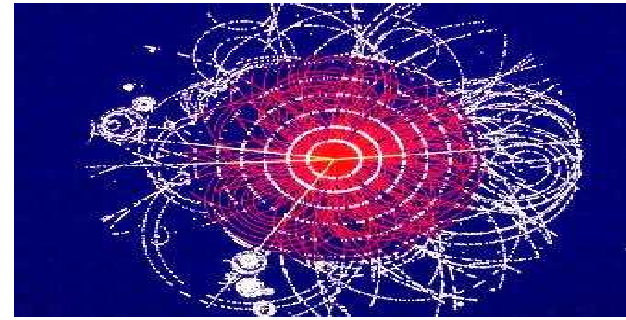
Combine different decay/production channels

Have a precise knowledge of S and B rates.

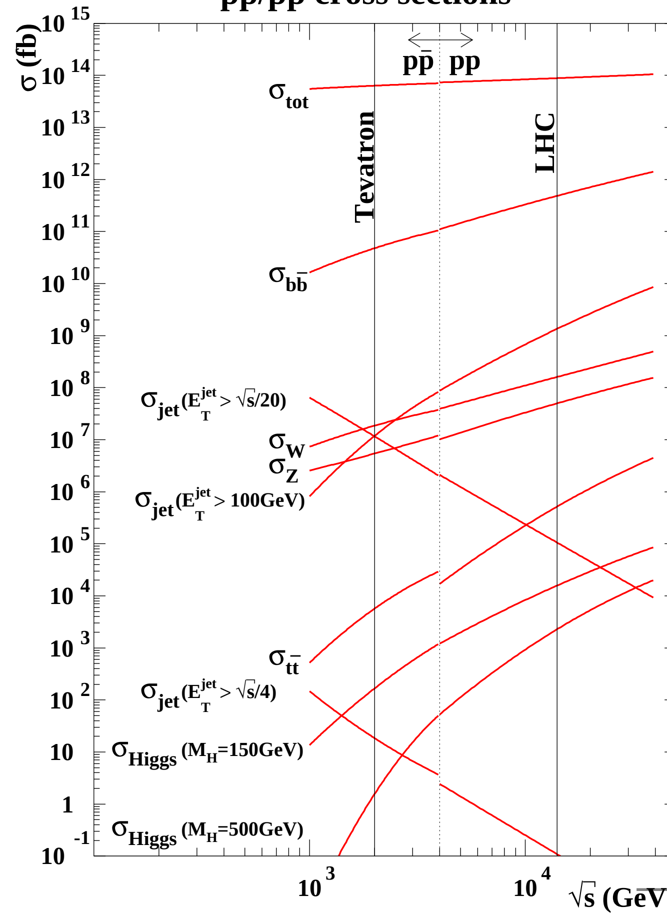
(note: higher orders can be factor of 2!)

- **Gigantic experimental (+theoretical) efforts**

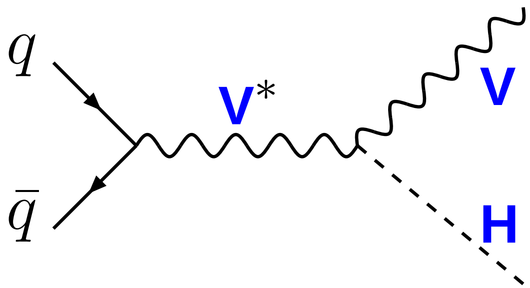
(more than 20 years of very hard work!)



pp/p$\bar{\text{p}}$ cross sections



4. Higgs at the LHC: associated HV



Similar to $e^+e^- \to HZ$ at LEP2.

$\sigma \propto \hat{s}^{-1}$ sizable if $M_H \lesssim 2M_Z$.

$\sigma(W^\pm H) \approx 2 \times \sigma(ZH)$.

Simply Drell–Yan for $q^2 \neq M_V^2$

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

Radiative corrections needed:

– for precise determination of σ

– stability against scale variation

$\Rightarrow$ radiative corrections $\approx$ those of DY

(at 2-loop need to consider $gg \to HZ$)

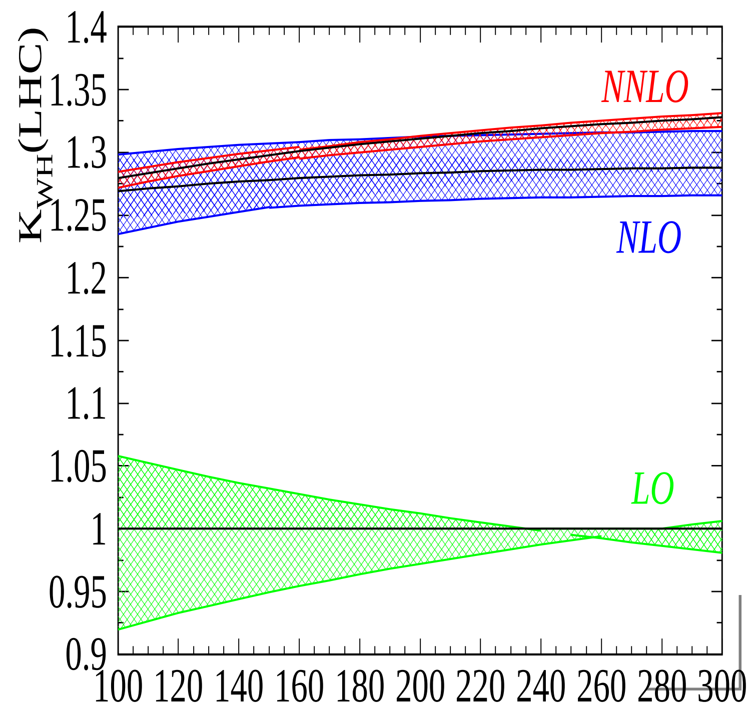
RC parameterized by K–factor:

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

Can also define K-factor at LO.

QCD RC known up to NNLO.

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



M_H [GeV]

4. Higgs at the LHC: associated HV

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

Signals: $\mathbf{WH} \to \gamma\gamma\ell\nu, \mathbf{b\bar{b}}\ell\nu, \mathbf{3}\ell$ **and** $\mathbf{ZH} \to \nu\nu\mathbf{b\bar{b}}, \ell\ell\mathbf{b\bar{b}}$.

ATLAS+CMS: 5σ **discovery of** $\gamma\gamma\ell\nu$ **with** $\mathcal{L} \gtrsim 100$ **fb.**

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

$\mathbf{H} \to \mathbf{b\bar{b}}$ **using jet–substructure?**

VH channel important at Tevatron:

$\mathbf{M_H \lesssim 130\,GeV : H \to bb :}$

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

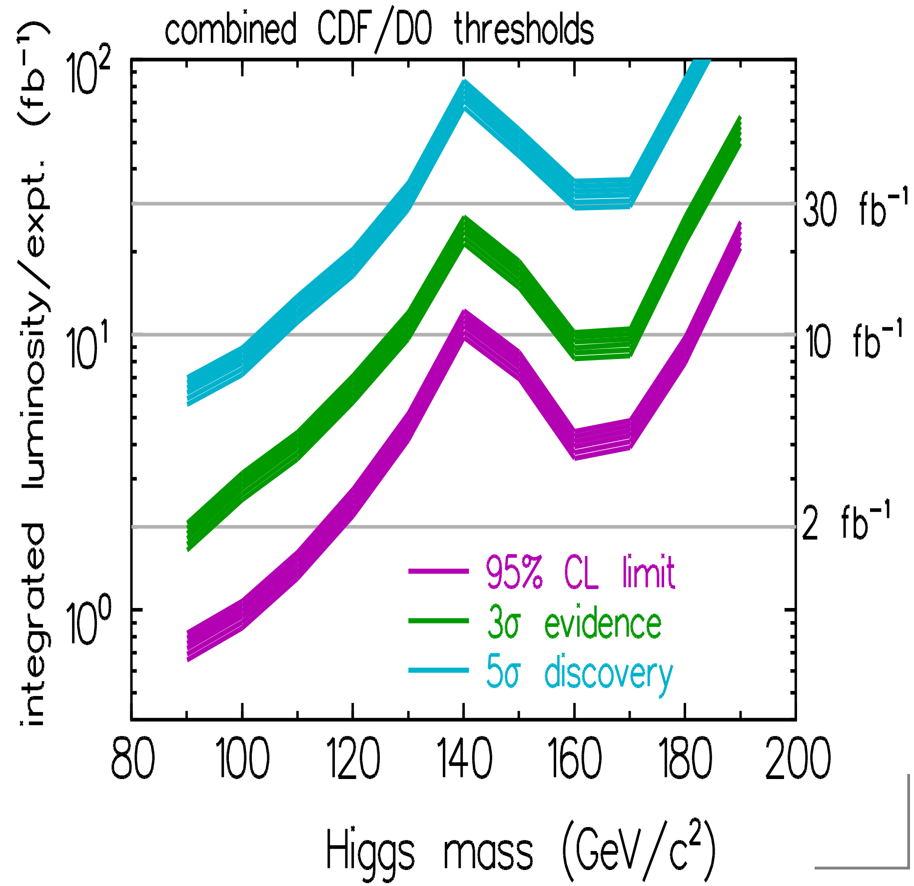
$\mathbf{M_H \gtrsim 130\,GeV : H \to WW^*}$

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

(report of Tevatron Higgs WG.)

CDF/D0 are getting very close!

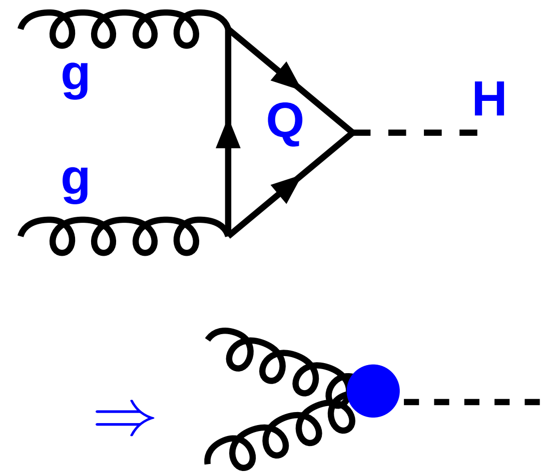
(included in 160–170 GeV excl.)



4. Higgs at the LHC: gg fusion

- Related to $\mathrm{H} \to \mathrm{gg}$: s $\hat{\sigma}_{\rm LO} \propto \Gamma_{\rm LO}$
- top loop dominant (b-loop $\lesssim 10\%$).
- $\mathcal{L}_{\rm gg}, \alpha_{\rm s}, \mathrm{g_{Htt}}$ large: $\Rightarrow$ **leading at LHC**
- For $\mathrm{m_Q} \to \infty$: finite amplitude
- approx $\mathrm{m_Q} \to \infty$ valid for $\mathrm{M_H} \lesssim 2\mathrm{m_t}$.

$\Rightarrow$ **EFT with t integrated out**



- Very large QCD corrections:

– exact NLO: $\mathrm{K_{NLO}} \approx 1.7$

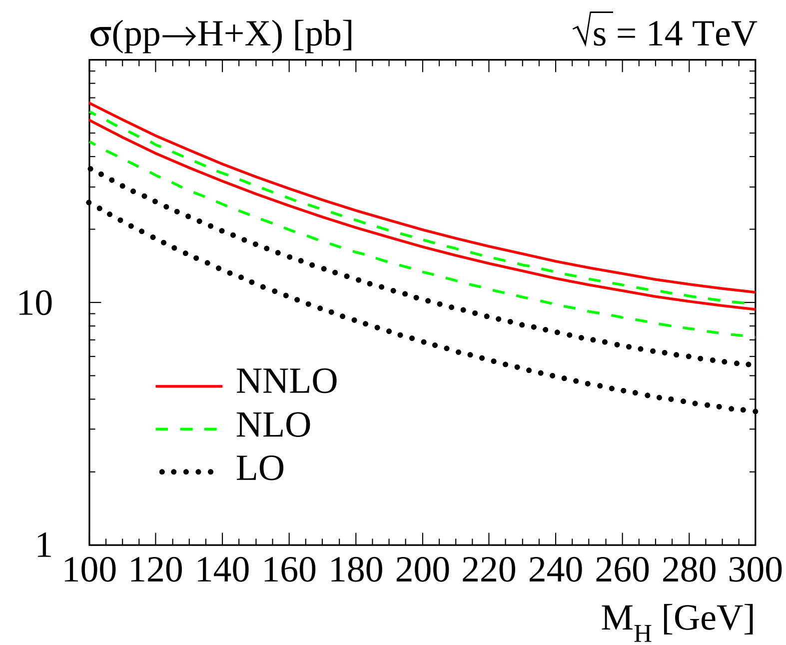
– EFT at NNLO: $\mathrm{K_{NNLO}} \approx 2$

– soft-gluon resum: $\approx +5\%$

– EW RC at $\mathcal{O}(\alpha_s \alpha) \approx 5\%$

- $\mathrm{P_T^{Higgs}} = 0$ at LO, generated at NLO.

– QCD RC to distributions also known



4. Higgs at the LHC: gg fusion

Relevant detection signals

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

– large σ and small BR: many events left.

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

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

– measure $d\sigma/dM_{\gamma\gamma}$ on both sides of peak.

– $S/B = 1/30$ for $M_{\gamma\gamma} \sim 2$ GeV (good $\gamma\gamma$ res.).

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

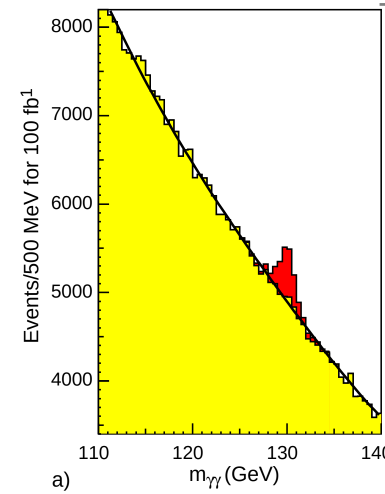
– large $\sigma \times \mathrm{BR}$ in this range but no $\mathrm{M_H^{recons}}$

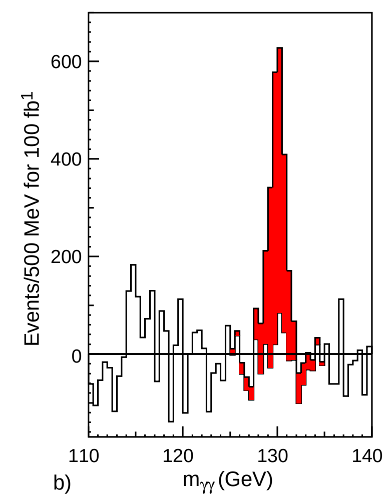
– large bkg from WW/tt but use spin-correlations!

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

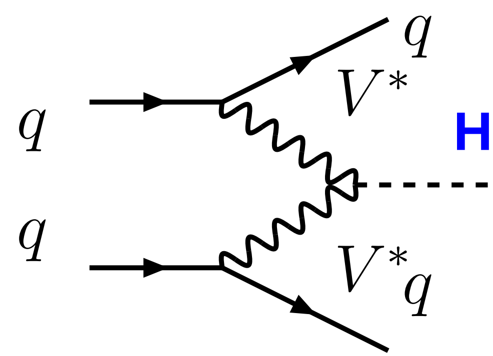
– gold plated mode, clean and small/measurable ZZ bkg.

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





4. Higgs at the LHC: WW fusion



- **Large rates: for small M_H and high $\sqrt{s}$**

  $\Rightarrow$ **2d most important process at LHC.**

– QCD radiative corrections small: order 10%.

– Small EW corrections: order -5%

– corrections for distrib. also known

- **Special kinematics of the process:**

– forward jet tagging: final jets forward peaked.

– have large energies $[\mathcal{O}$(1 TeV)] and $P_T[\mathcal{O}(M_V)]$.

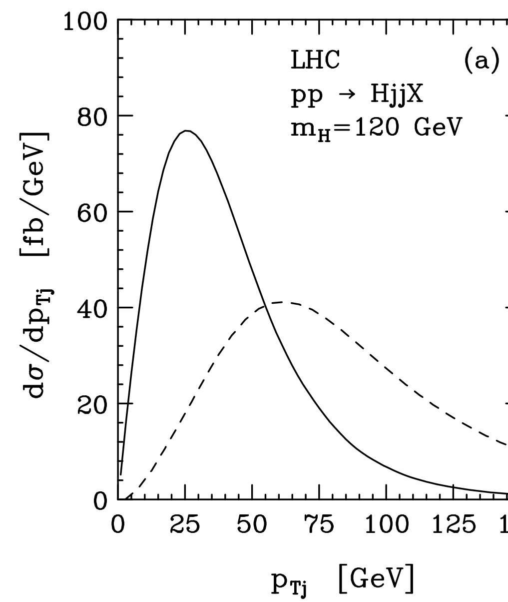
– central jet vetoing: H decays central/isotropic.

– small hadronic activity in central region (trigger).

$\Rightarrow$ **allow to suppress backgrounds; $S/B \sim 1$**

- **Clean and (theoretically) well under control:**

  $\Rightarrow$ **can be used for precision measurements**

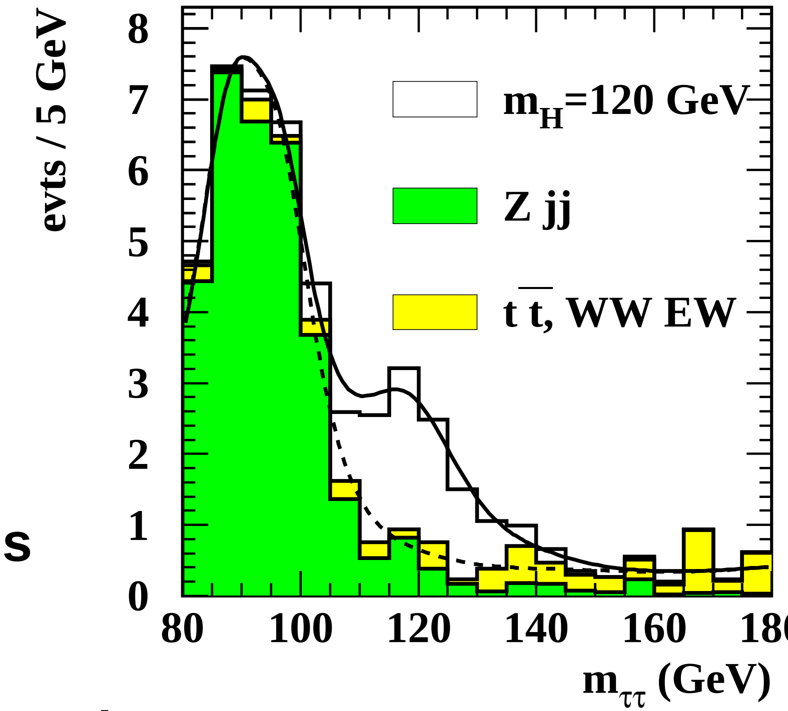


—— lowest/central je

– – highest/central je

4. Higgs at the LHC: WW fusion

Relevant detection signals



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

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

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

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

• $\mathrm{H}\to\gamma\gamma$ **for** $\mathrm{M_H}\lesssim 150$ **GeV:**

very clean with small/measurable bkgs

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

• $\mathrm{H}\to\mathrm{WW}\to\ell\ell\nu\nu$

very difficult as you need to know background.

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

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

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

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

4. Higgs at the LHC: Htt production

- Most complicated channel at LHC
- Smallest H production rates
- Sensitive directly to ttH coupling!

if $\mathrm{H} \to \mathrm{b\bar{b}}$ only femionic channels

- QCD corrections small: $\approx$ 20%

but σ^{NLO} very stable against scales...

Interesting signals at the LHC:

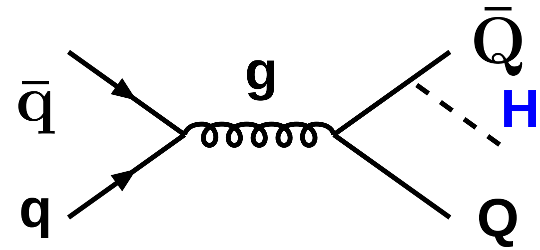
- $\mathrm{Htt} \to \gamma\gamma\ell^{\pm}$: clean but small rates.
- $\mathrm{Htt} \to \mathrm{b\bar{b}}\ell^{\pm}$: large jet bkg!
- $\mathrm{Htt} \to \ell^{\mp}\ell^{\pm}\nu\nu$: large ttWjj bkg...

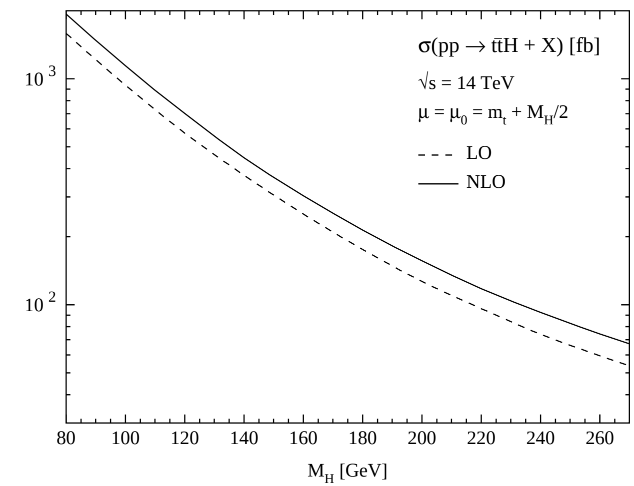
3–5σ signal at $\mathrm{M_H} \lesssim 140$ GeV for high $\mathcal{L}$

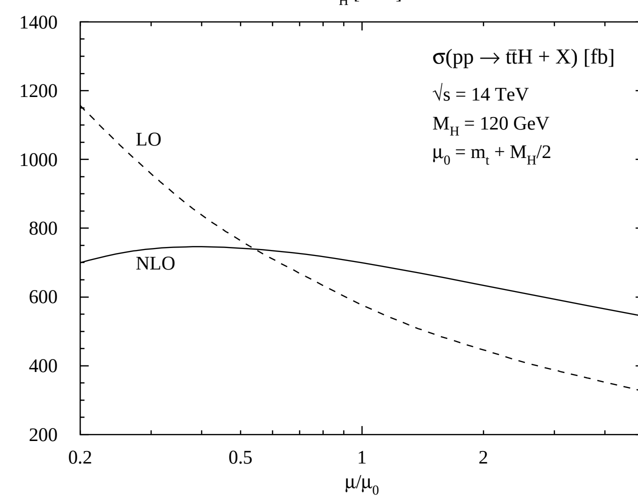
Combine with similar channels/topologies

(eg: $\mathrm{pp} \to \mathrm{WH} \to \ell\nu\gamma\gamma, \ell\nu\mathrm{b\bar{b}}$)

Jet substructure might help for H⟶bb

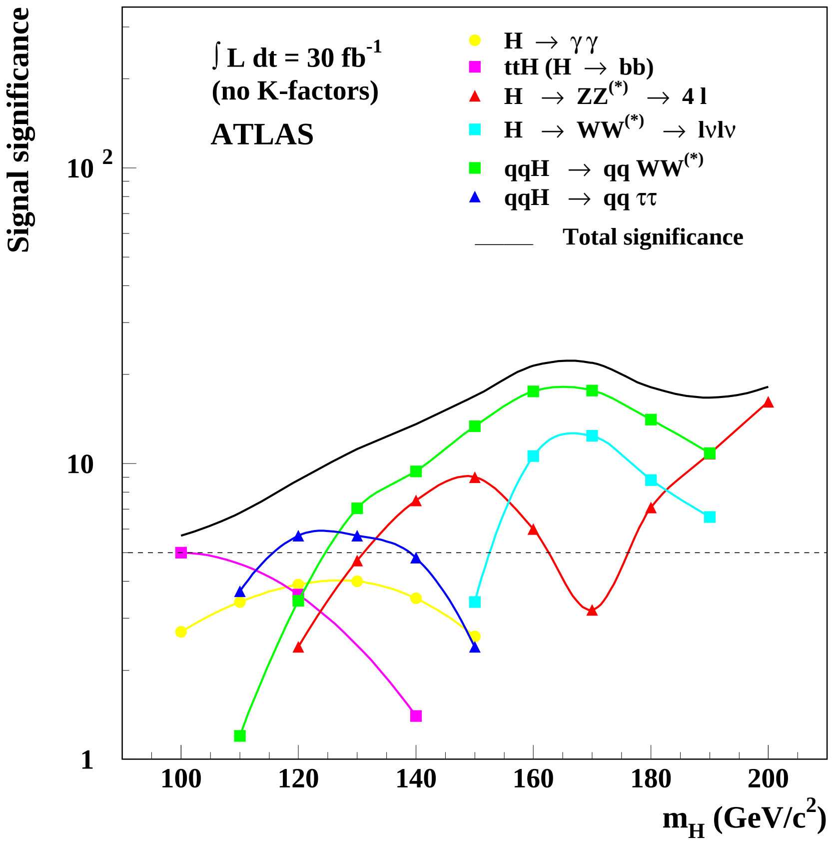


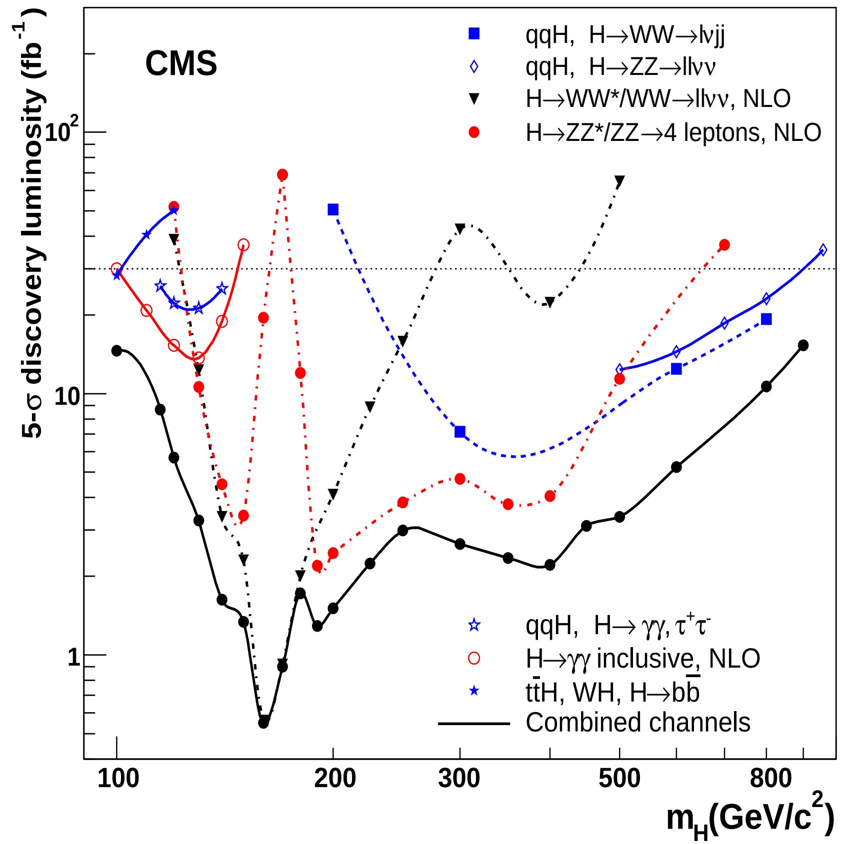




4. Higgs at the LHC: summary

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





5. The Higgs at the Tevatron and ℓHC

- $M_H \gtrsim 150$ GeV : $gg \to H$

(with $H \to W^*W^* \to \ell\ell\nu\nu$)

– exact NLO: $K \approx 2$ (1.7@LHC)

– EFT NNLO: $K \approx 3$ (2.0@LHC)

– EFT NNLL: $\approx +10\%$ (5%)

– exact NLO EW: $\approx \pm$ a few %

- $M_H \lesssim 150$ GeV : $q\bar{q} \to HV$

$q\bar{q} \to HW \to b\bar{b}\ell\nu$

$q\bar{q} \to HZ \to b\bar{b}\ell\ell, b\bar{b}\nu\bar{\nu}$

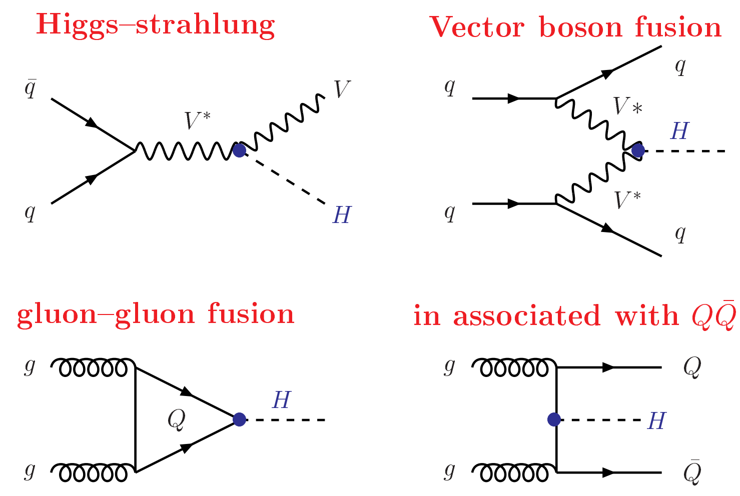
$q\bar{q} \to HW \to \ell\ell\ell\nu\nu\nu$

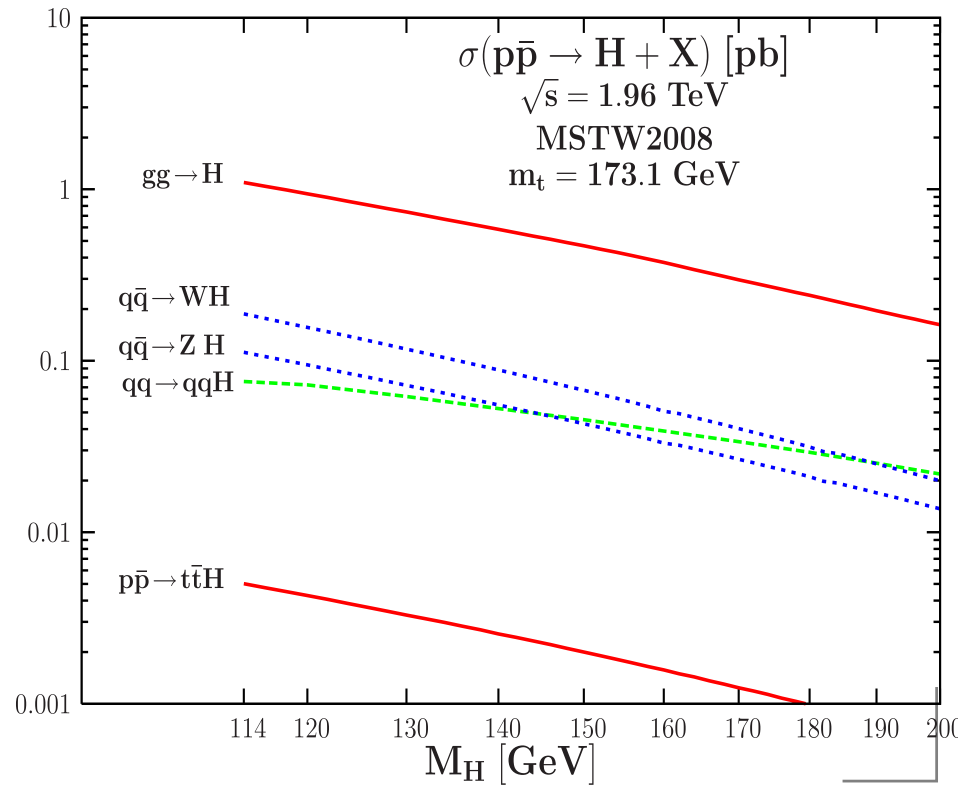
exact NNLO QCD: $K \approx 1.5$

exact NLO EW: $\approx -5\%$

In practice combine ggH+HZ/HW

- $p\bar{p} \to Hqq$: bkg. too high.
- $p\bar{p} \to Ht\bar{t}$: rates too low.





5. Higgs at the Tevatron: $gg \to H$

- **K factors very large:**

good: Tevatron sensitive to $\rm H_{SM}$!
bad: perturbation theory in danger
uggly: HO corrections important...

- **Analysis of theory errors on σ:**

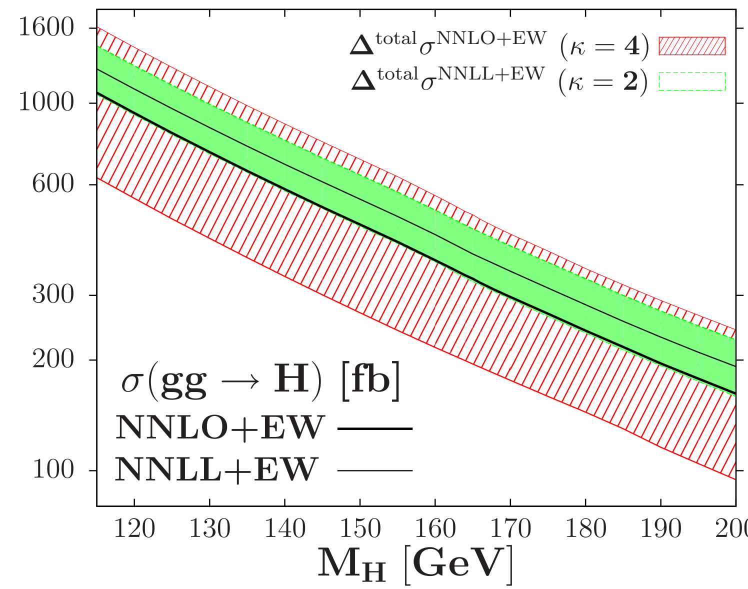
– from scale: $\frac{M_H}{3} \le \mu_{F/R} \le 3M_H$
very important (HO large) $\approx$ 20%
– PDFs: small within given param.
but # param. large spread $\approx$20%
– Difference due to $\Delta^{\rm exp+th}\alpha_s$:
$\alpha_s(M_Z^2)$=0.1171$\pm$0.0034$\pm$0.003
– Use of EFT for $\sigma^{\rm NNLO}$: $\approx$5%

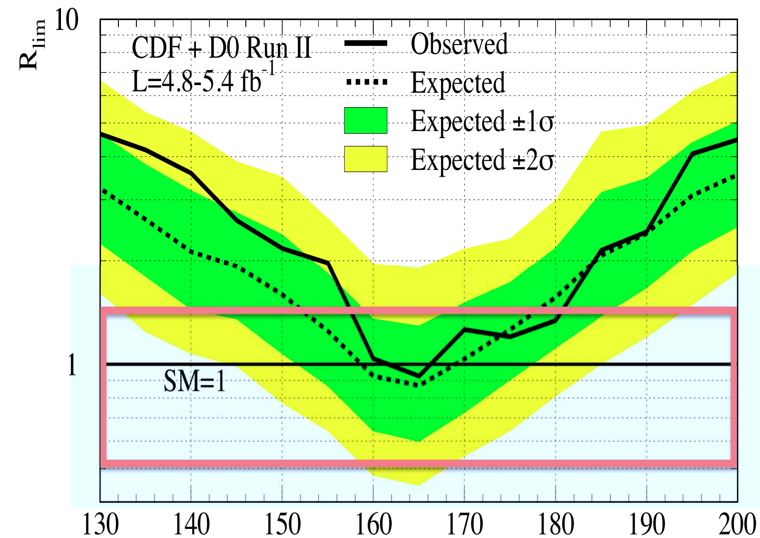
- **Combine all theory errors:**

– PDFs on $\sigma^{\rm max}_{\rm min}$ + EFT $\approx$40%
– CDF/D0 assign only 10% error

- **Same for HV: $\approx$10% error**

Baglio+AD (2010)





CDF/D0 exclusion range M_H=162–166 GeV needs to be reconsidered.

5. The Higgs at the LHC at the ℓHC

ℓ**HC:** $\sqrt{s}=7$ TeV, $\int\mathcal{L}=1\ \text{fb}^{-1}$

Same production as at Tevatron:

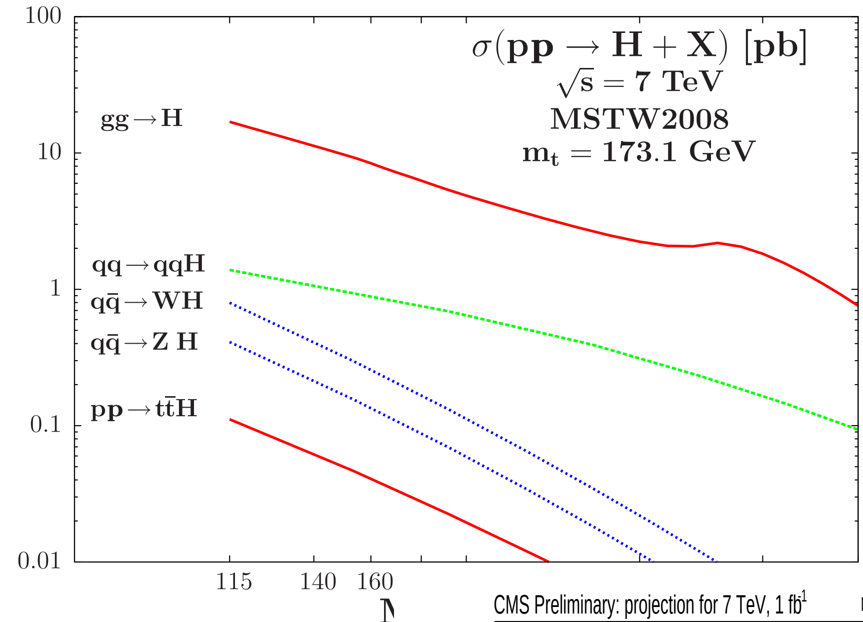
– rates $\approx$ 10 times higher

– much larger backgrounds

– much lower luminosity: $1\ \text{fb}^{-1}$

Only: $gg\to H\to W^*W^*\to\ell\ell\nu\nu$

($\approx$ 200 of Higgs signal events)

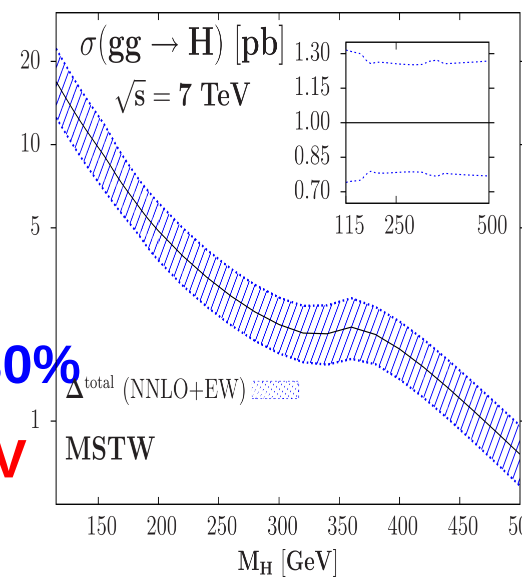


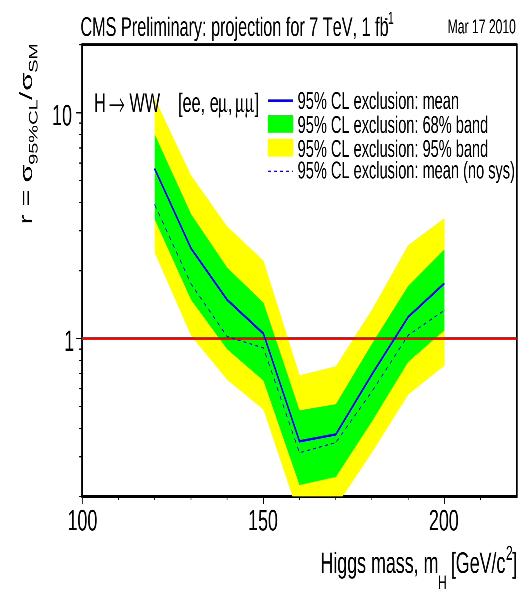
Compared to the Tevatron case:

- **Smaller HO:** $K_{NNLO}=2,5$
- **Scale:** κ**=2 enough $\Rightarrow$ 15%**
- **PDF errors smaller, $\approx$10%**
- **Again 5% error from EFT**

Combined uncertainty $\approx\pm$25–30%

excludes $M_H\approx150-190$ GeV





6. 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/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**

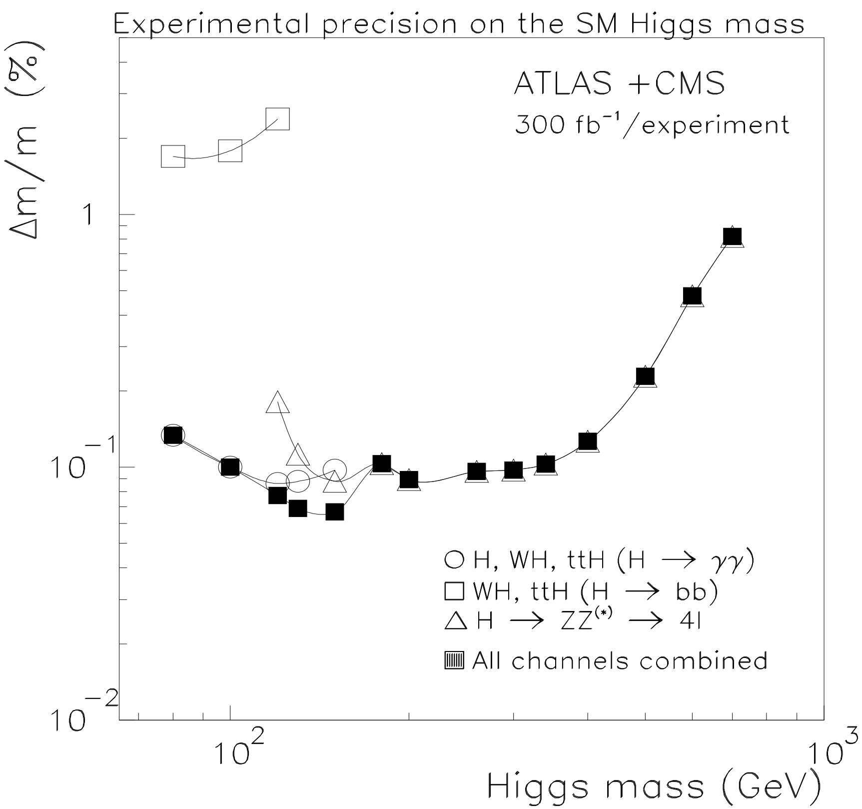
Final $\Delta \mathrm{M_H}/\mathrm{M_H} \sim 0.1\%$ to 1%.

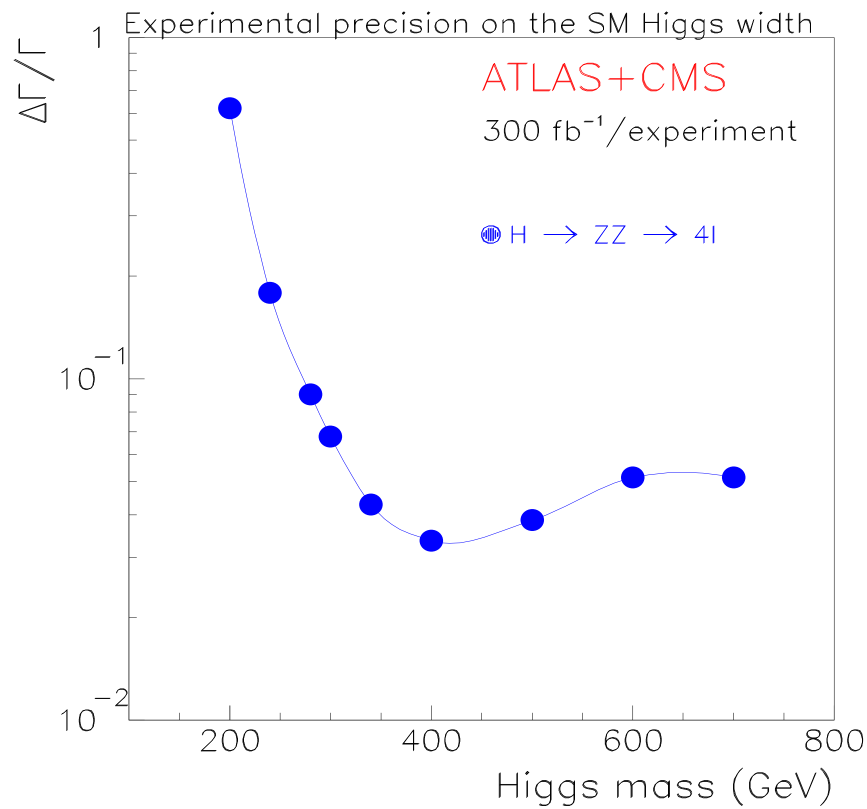
Higgs boson total width:

– **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: J^{PC} numbers

• Higgs spin:

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

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

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

• Higgs parity:

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

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

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,

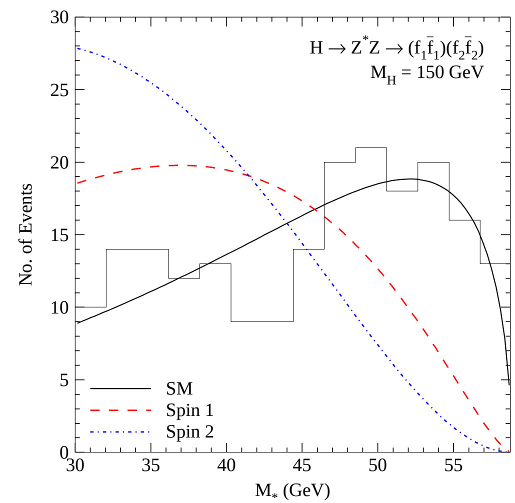
rates for $A \to VV$ **are too small...**

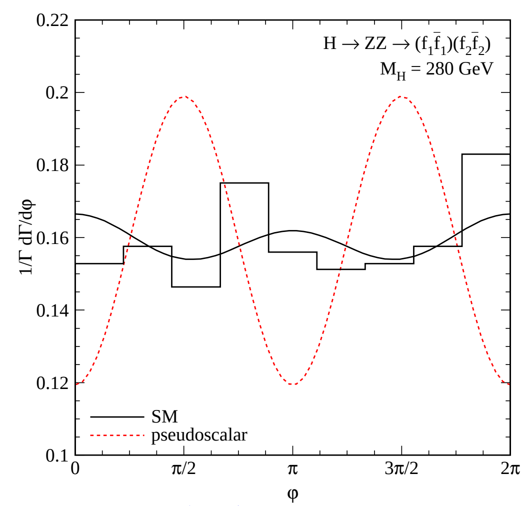
More convincing: look at Hff couplings

Possible but challenging channels:

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

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





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

6. Higgs properties: Higgs couplings

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

LHC with $\mathcal{L} = 300\mathrm{fb}^{-1}$ (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 $\mathrm{g_{Htt}}$

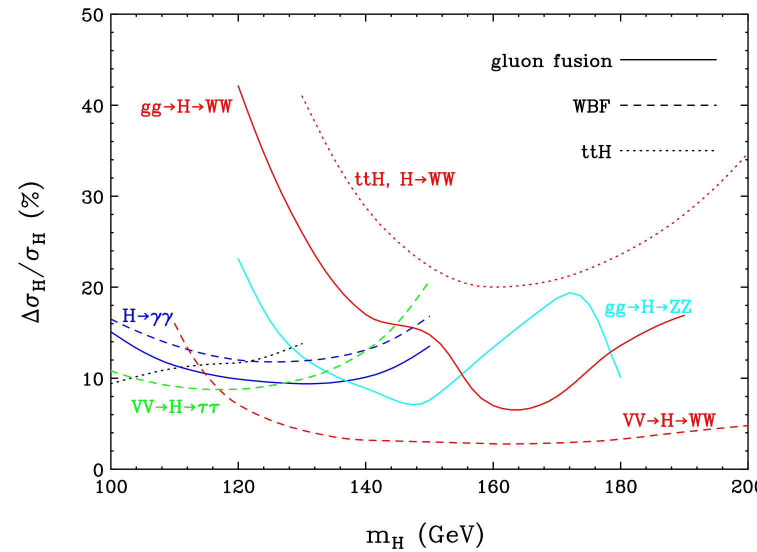
$\Rightarrow$ ratios of $\sigma \times \mathrm{BR}$: many errors drop out!

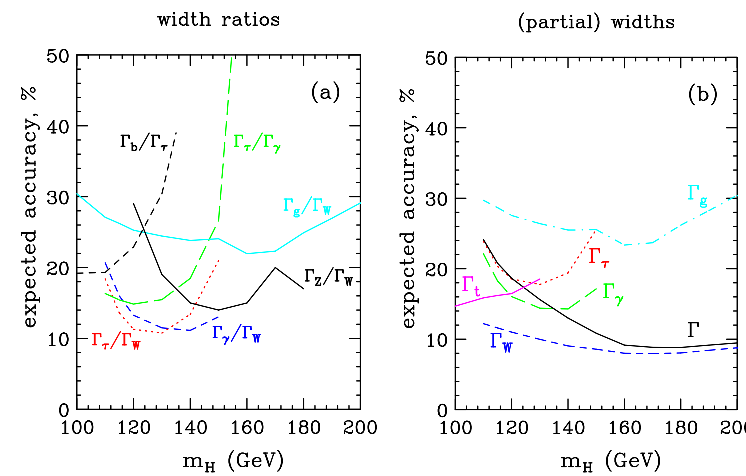
• One obtains width ratios: $\Gamma_\mathrm{X}/\Gamma_\mathrm{Y}$

• 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%





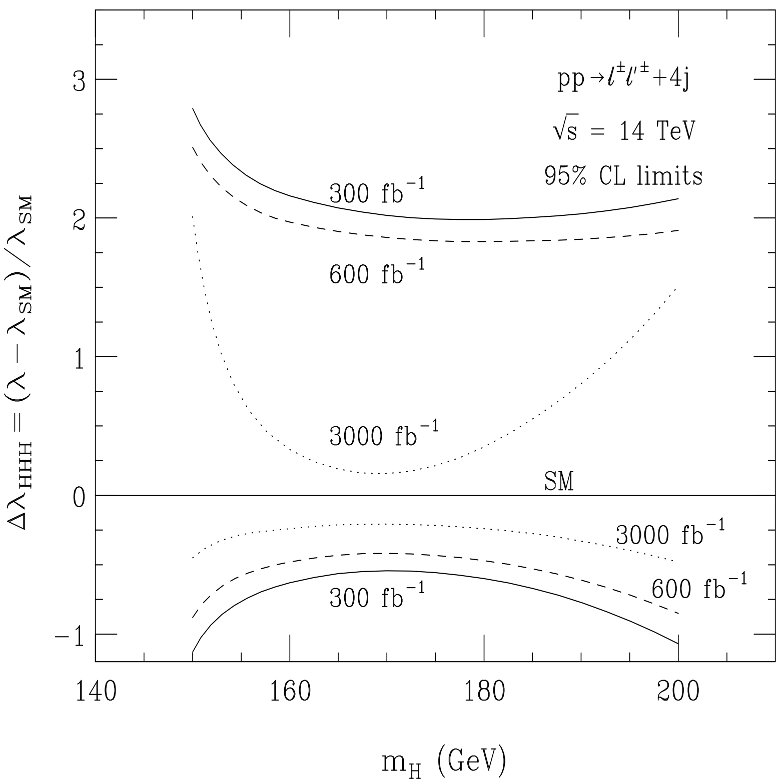
6. Higgs properties: Higgs self-couplings

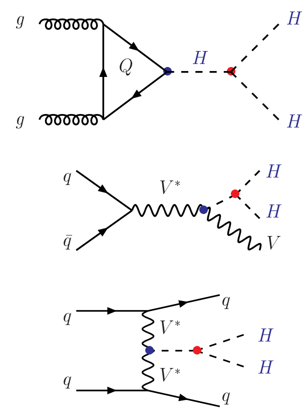
Important couplings to be measured: $g_{H^3}, g_{H^4} \Rightarrow$ access to V_H.

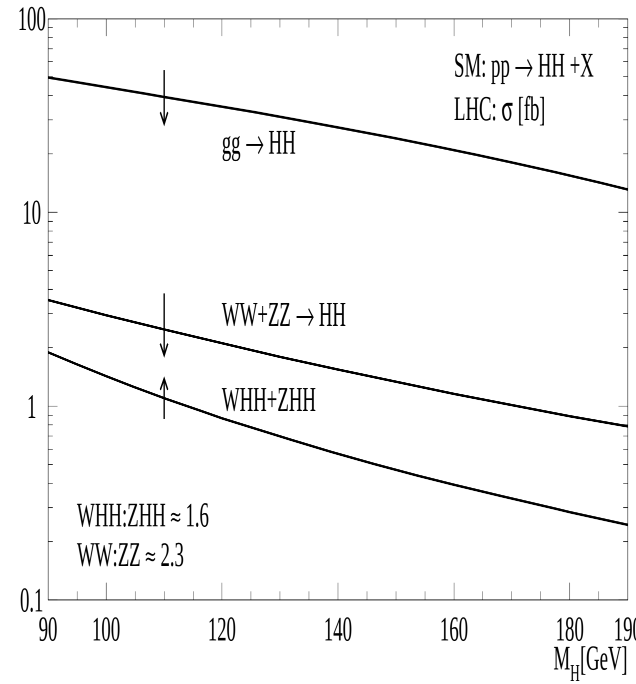
- g_{H^3} from $pp \to HH + X \Rightarrow$
- g_{H^4} from pp→3H+X, hopeless.

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. EWSB in SUSY

The SM has many attractive theoretical/experimental features:

- **Based on gauge principle, unitary, perturbative, renormalisable $\cdots$**
- **Once $\mathrm{M_H}$ fixed: everything is predictible with great accuracy.**
- **And has passed all experimental tests up to now.**

But the model has too many shortcomings:

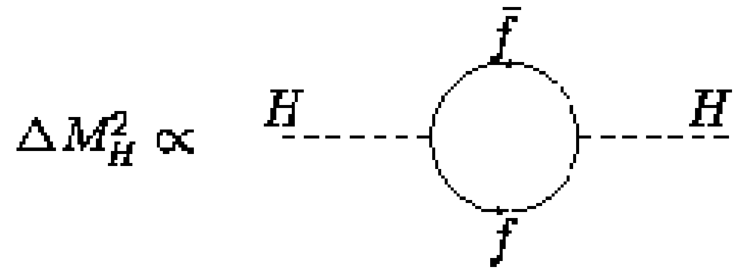
- **Too many free parameters (19!) in the model, put by hand...**
- **Does not include the fourth fundamental force, gravity, ..**
- **Does not say anything about the masses of the neutrinos.**
- **No real unification of the three gauge interactions.**
- **Does not explain the baryon asymmetry in the universe.**
- **There is no stable, weak, massive particle for dark matter.**
- **No satisfactory explanation for $\mu^2 < 0$ (put ad hoc).**

And above all that, there is the hierarchy or naturalness problem.

7. EWSB in SUSY: the SM hierarchy problem

- **Radiative corrections to M_H^2 in SM**

with a cut–off $\Lambda = M_{NP} = M_{GUT}$



$$\Delta M_H^2 = N_f \frac{\lambda_f^2}{8\pi^2}\left[-\Lambda^2 + 6m_f^2 \log\frac{\Lambda}{m_f} - 2m_f^2\right] + \mathcal{O}(1/\Lambda^2)$$

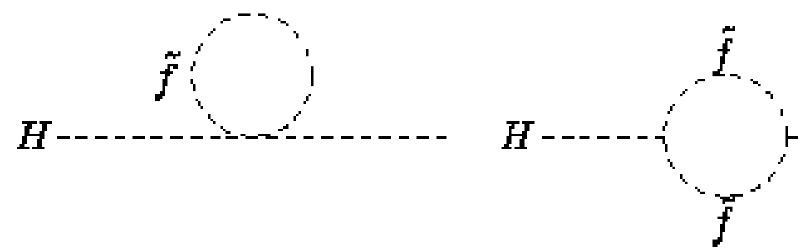
M_H prefers to be close to the high scale than to the EWSB scale,

unless an extreme parameter fine tunning is made (also problematic).

$\Rightarrow$ there is no symmetry to protect M_H in the SM ($\neq$ fermions, photon, ..).

- **Add scalar partner contribution:**

$$N_S = N_f,\ \lambda_f^2 = -\lambda_S,\ m_1 = m_2 = m_S$$



$$\Delta M_H^2\big|^{\rm tot} = \frac{\lambda_f^2 N_f}{4\pi^2}\left[(m_f^2 - m_S^2)\log\left(\frac{\Lambda}{m_S}\right) + 3m_f^2 \log\left(\frac{m_S}{m_f}\right)\right]$$

$\Rightarrow$ Symmetry between fermions–scalars $\Rightarrow$ no divergence in Λ^2

"Supersymmetry" no divergences at all: M_H is protected!

Note that if $m_S \gg m_f$ ($\gtrsim$ 1 TeV) the fine tunning problem is back!!!

7. EWSB in SUSY: SUSY and the MSSM

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

(see the Lectures by R. Godbole)

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

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

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

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

Focus on: Minimal Supersymmetric Standard Model (MSSM):

- **minimal gauge group: SU(3)$\times$SU(2)$\times$U(1),**
- **minimal particle content: 3 fermion families and 2 Φ doublets,**
- **R=$(-1)^{(2s+L+3B)}$ parity is conserved,**
- **minimal set of terms (masses, couplings) breaking "softly" SUSY.**

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

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

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

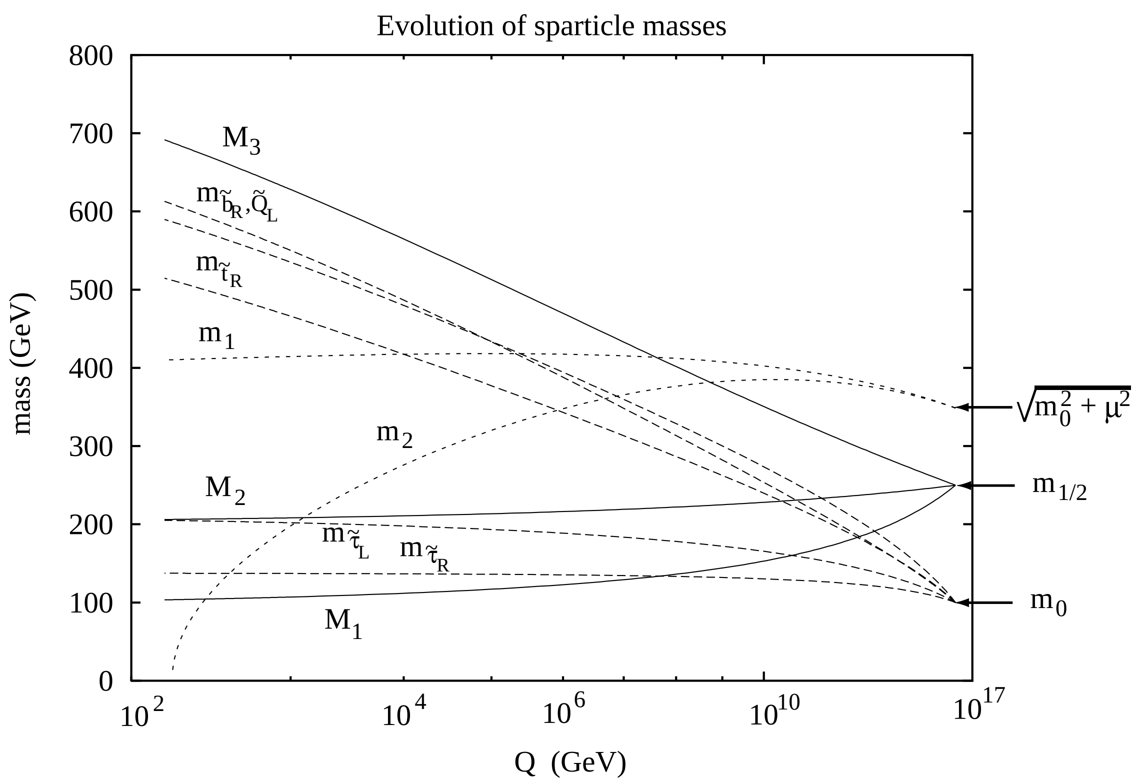
– constrained models with universal boundaries, very few parameters

7. EWSB in SUSY: symmetry breaking

mSUGRA: Only 4.5 param: $\tan\beta$, $\mathbf{m_{1/2}}$, $\mathbf{m_0}$, $\mathbf{A_0}$, $\mathrm{sign}(\mu)$

All soft breaking parameters at $\mathrm{M_S}$ are obtained through RGEs.

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



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

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

8. The MSSM Higgs sector

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

- **to cancel the chiral anomalies introduced by the new** $\tilde{\mathrm{h}}$ **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:**

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

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

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

We have important constraint on the MSSM Higgs boson masses:

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

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

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

8. The MSSM Higgs sector: Higgs masses

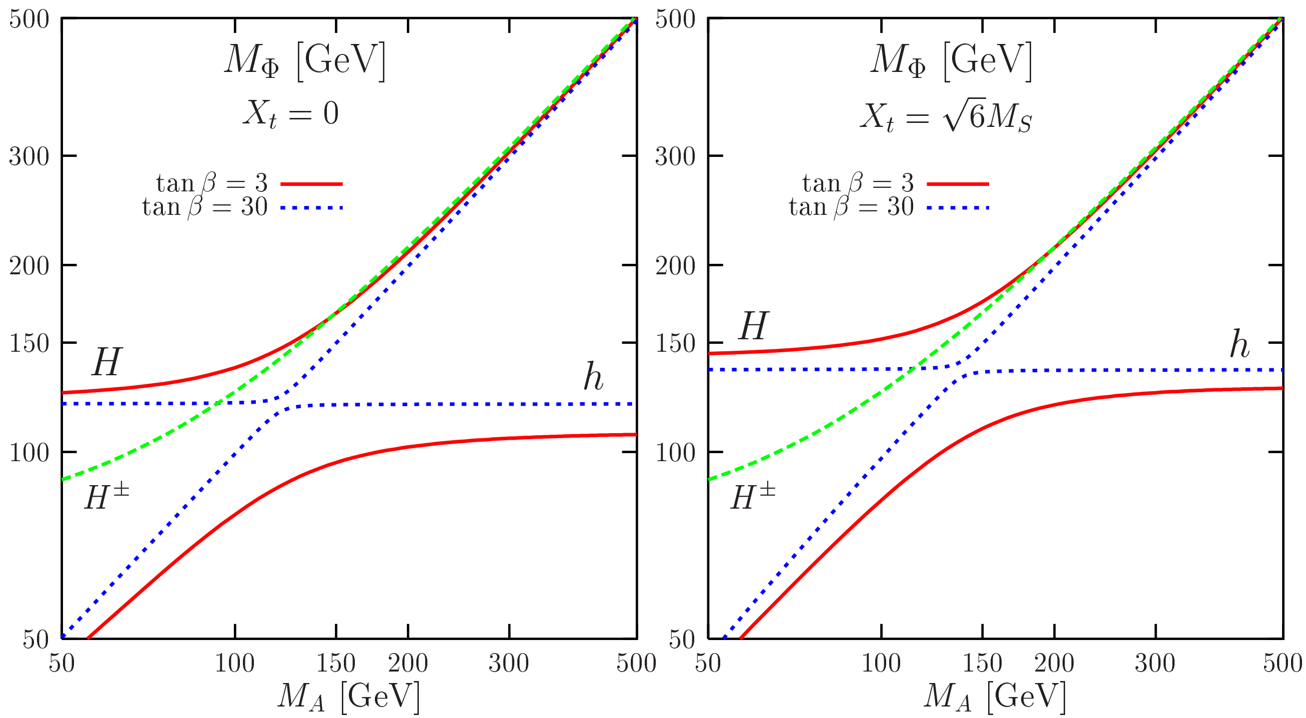
Radiative corrections very important in the MSSM Higgs sector.

See talk by Thomas Hahn on FeynHiggs

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

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

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



8. 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.**

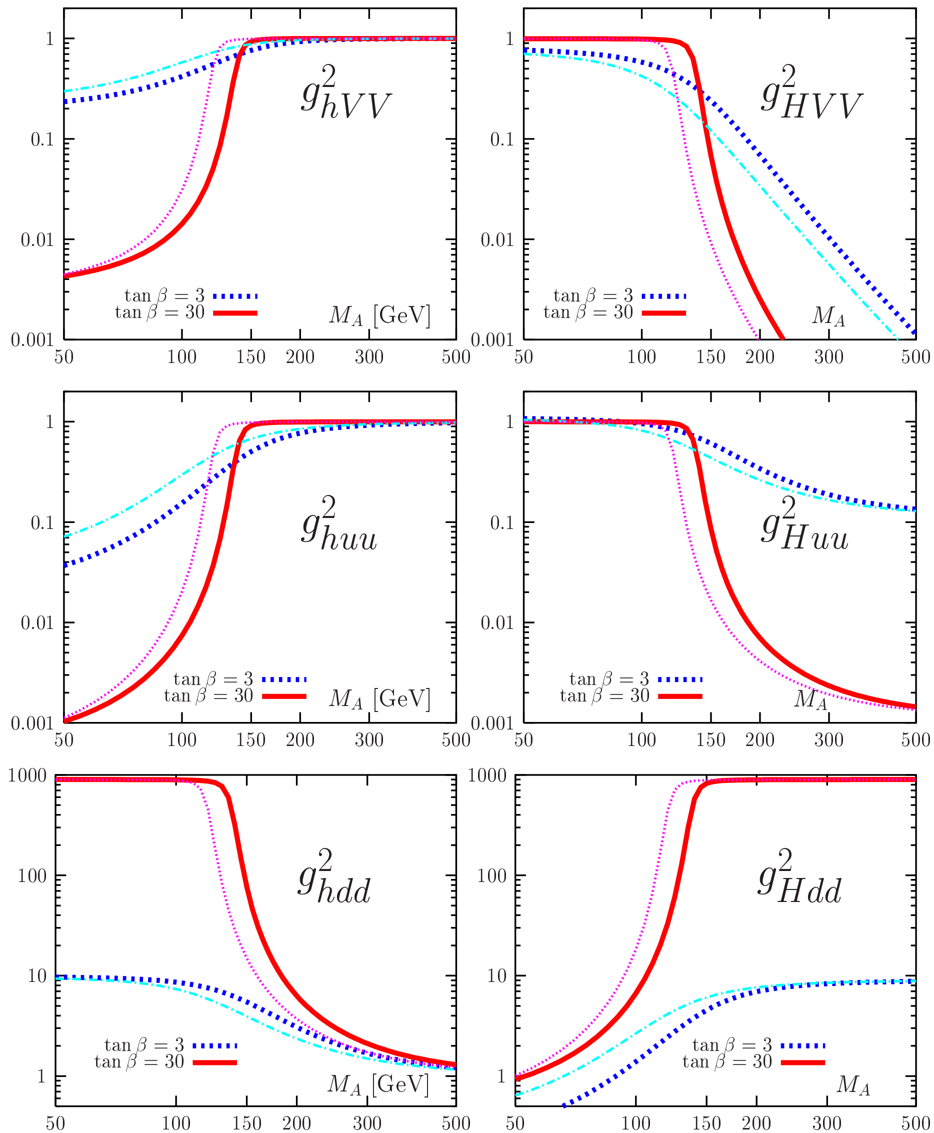
– **For $\tan\beta \gg 1$: couplings to b quarks ($\mathrm{m_b}\tan\beta$) very strong.**

– **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.

8. The MSSM Higgs sector: SUSY Higgs couplings

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



8. The MSSM Higgs sector: beyond the conventional MSSM

Giving up some assumptions: the example of the CP–violating 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....)

$\Rightarrow$ h, H,A are not CP definite states: h_1, h_2, h_3 are CP mixtures

determination of Higgs spectrum slightly more complicated than usual

Additional Higgs representations: the example of the NMSSM

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

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

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

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

less fine-tuning, richer phenomenology, interesting constrained version, ..

Both lead to a possibly very light Higgs that has escaped detection!

8. The MSSM Higgs sector: Higgs 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**

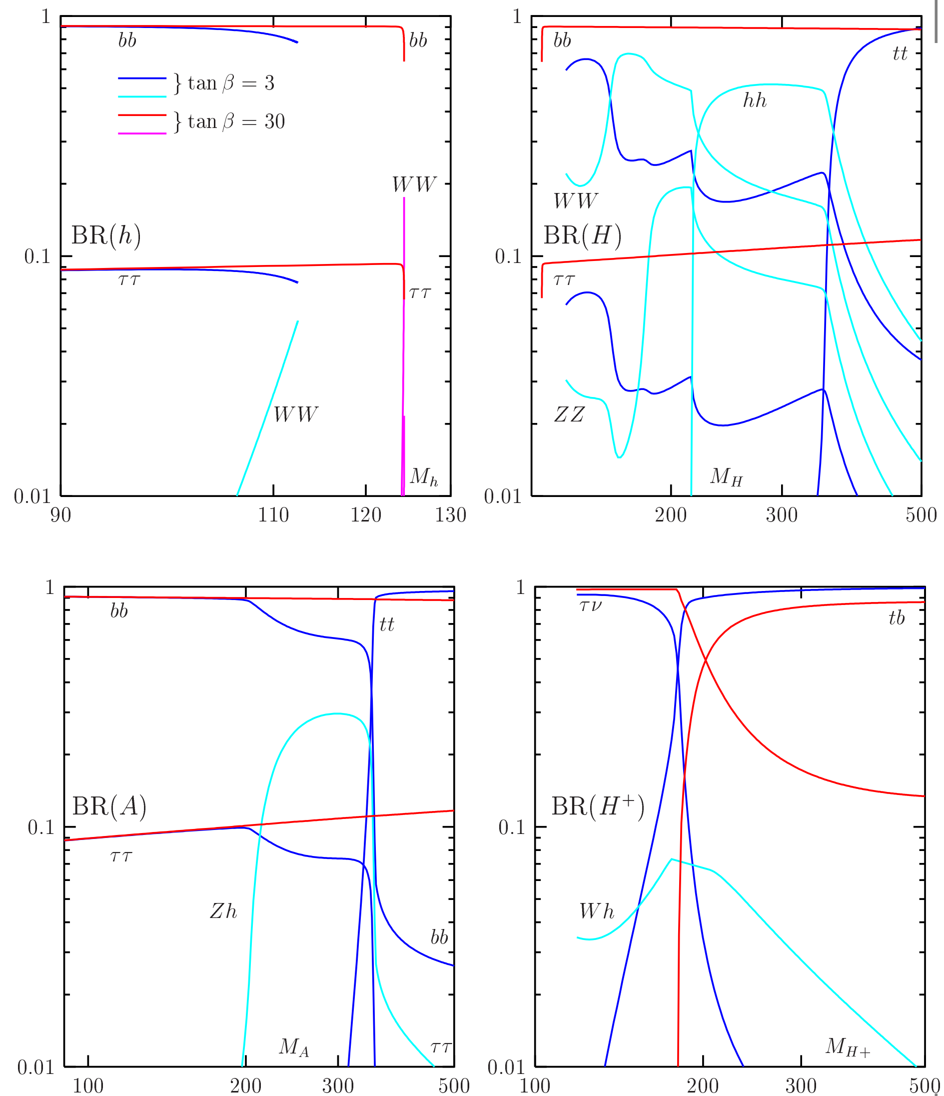
$(\mathrm{WW}, \mathrm{ZZ}, \mathrm{hh}$ **decays suppressed).**

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

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

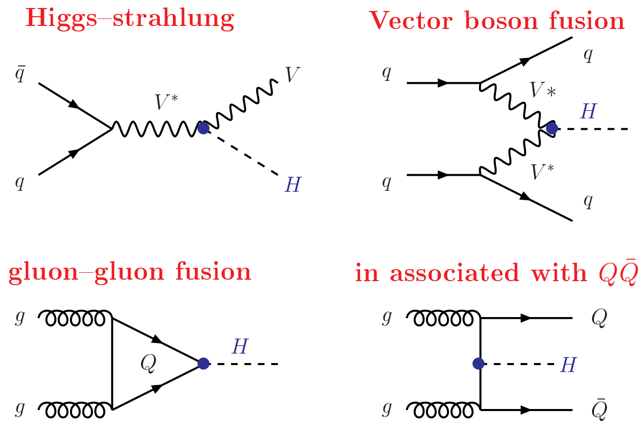
Possible new effects from SUSY

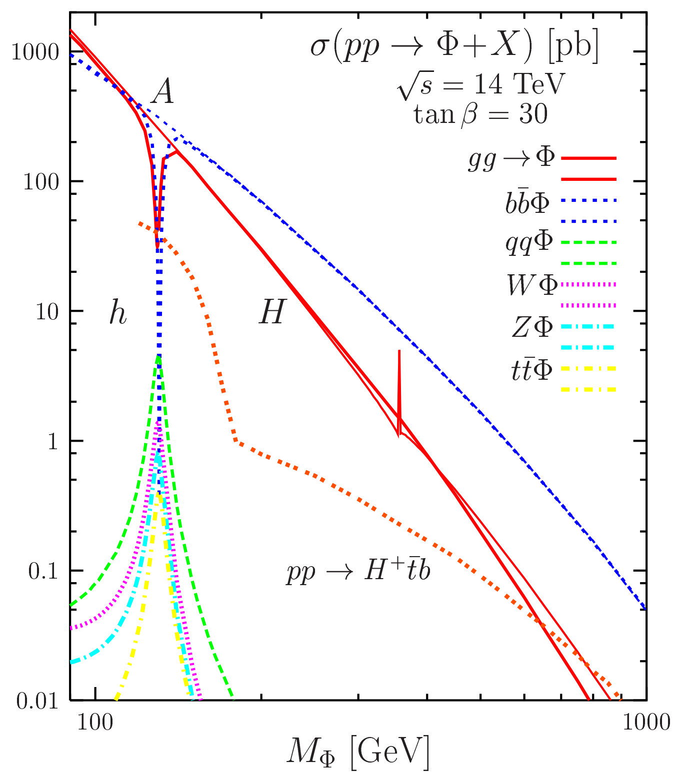
Note: total decay widths small....



9. SUSY Higgses at the LHC: production rates

SM production mechanisms





What is different in MSSM

- **All work for CP–even h,H bosons.**
- **– in ΦV, $qq\Phi$ h/H complementary**
- **– $\sigma(\mathrm{h}) + \sigma(\mathrm{H}) = \sigma(\mathrm{H_{SM}})$**
- **– additional mechanism: qq $\longrightarrow$ A+h/H**
- **For $\mathrm{gg} \to \Phi$ and $\mathrm{pp} \to \mathrm{tt}\Phi$**
- **– include the contr. of b–quarks**
- **– dominant contr. at high tanβ!**
- **For pseudoscalar A boson:**
- **– CP: no $\Phi\mathrm{A}$ and qqA processes**
- **– $\mathrm{gg} \to \mathrm{A}$ and $\mathrm{pp} \to \mathrm{bbA}$ dominant.**
- **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 $\mathrm{pp} \to \mathrm{t\bar{b}H^-}$**

9. SUSY Higgses at the LHC: higher orders

Summary of higher order calculations in MSSM (for SM see earlier)

For h/H: same processes as for SM Higgs (esp. for $M_A \gg M_Z$) but:

- Include b–loop contributions to $gg \to h/H$ and new $gg \to A$

K–factors only at NLO ($\sim$ 1.5–2)

- Include b–final states in $pp \to b\bar{b} + h/H$ (dominant at high $\tan\beta$)

large K–factors at NLO (50%)

- Additional SUSY–QCD corrections in $pp \to V + h/H ; qq + h/H$:

rather small at NLO (a few %) for heavy $\tilde{q}/\tilde{g}$

For A: rates including K–factors approx the same as above for h/H

For $H^\pm$: main process is $pp \to tt^{(*)} \to tbH^\pm$ in general

relevant corrections known exactly at NLO

h,H,A,$H^\pm$ decays: well under control including SUSY+NLO corrections

summarized in the program HDECAY

9. SUSY 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

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

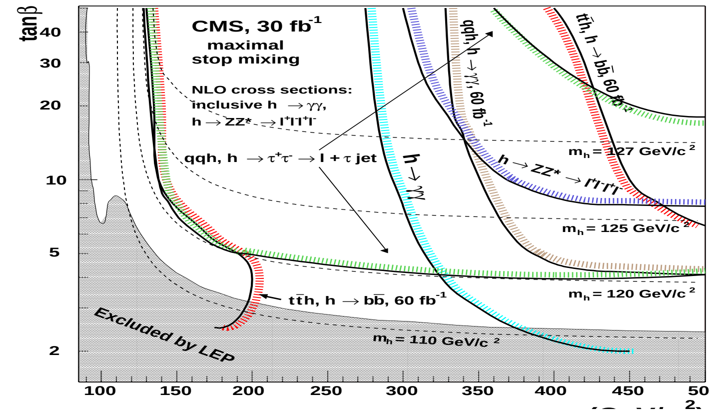
(as in SM for H in anti-decoupling regime).

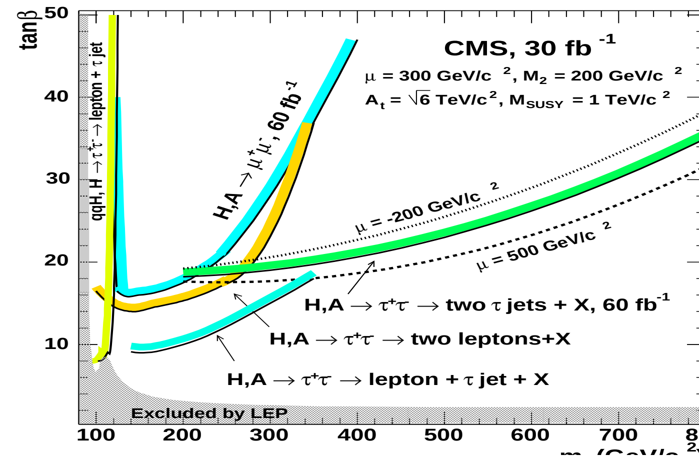
The charged Higgs:

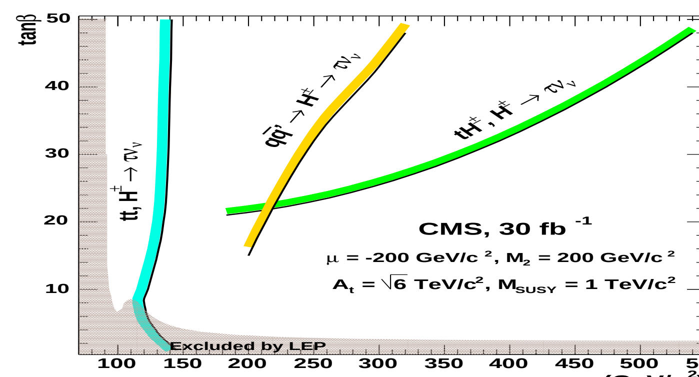
$$t \to bH^- \to b\tau\nu \text{ for } M_H \lesssim m_t$$

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

reach depends on M_A and tanβ

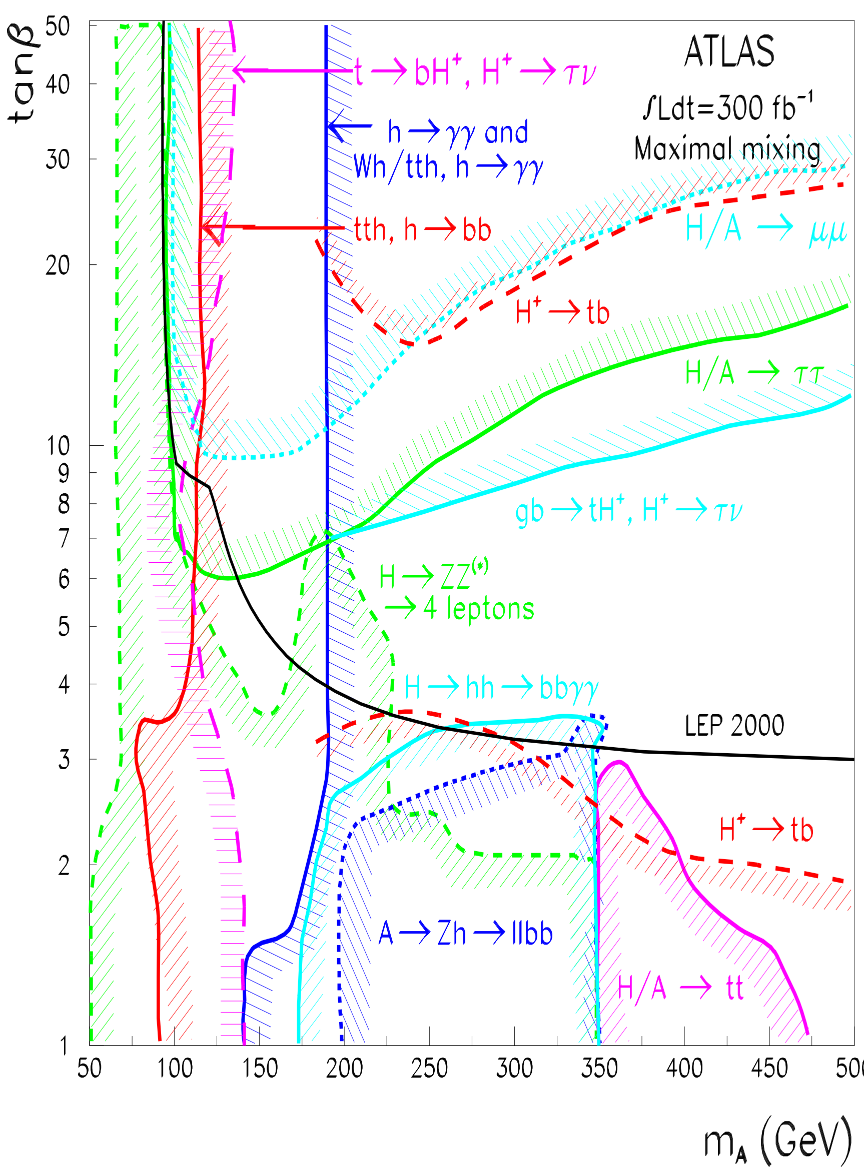


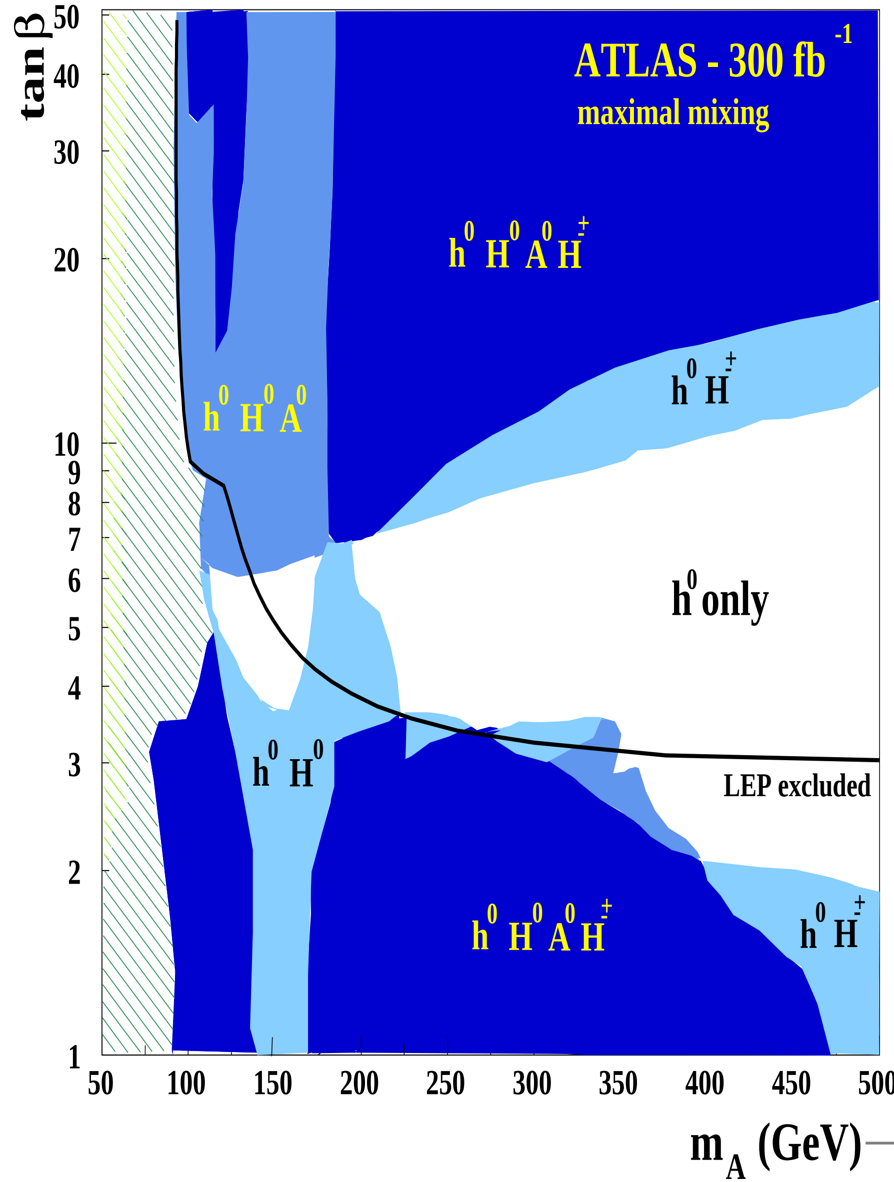




9. SUSY Higgses at the LHC: detection

Slightly outdated but still telling......





9. SUSY Higgses at the LHC: measurements

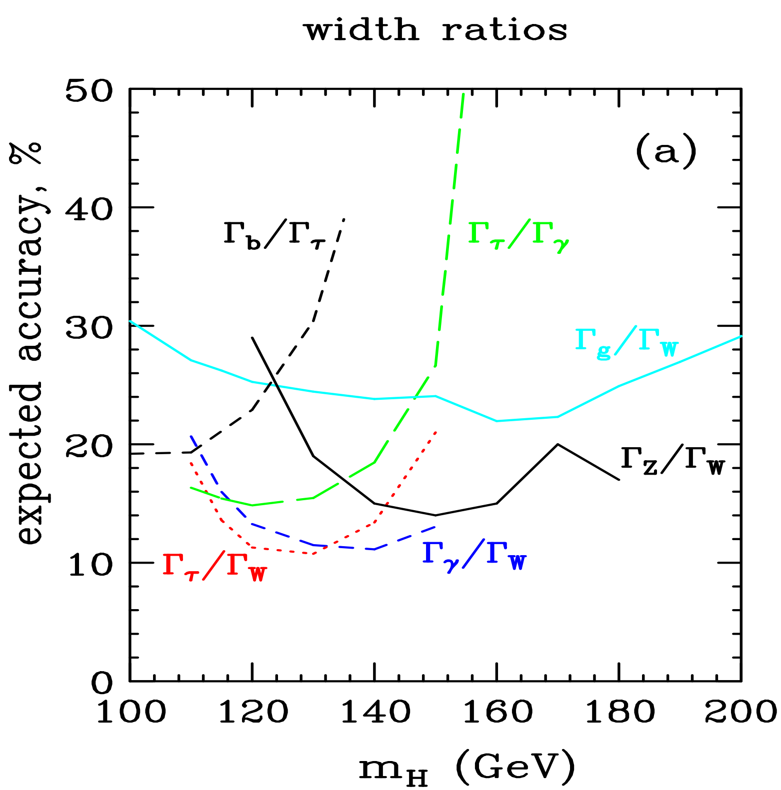
Lightest Higgs: as in SM

Higgs mass $h \to \gamma\gamma, ZZ^*$

Higgs couplings from $\sigma \times$ **BR**

Higgs spin+CP numbers: hard

Higgs self-couplings hopeless...

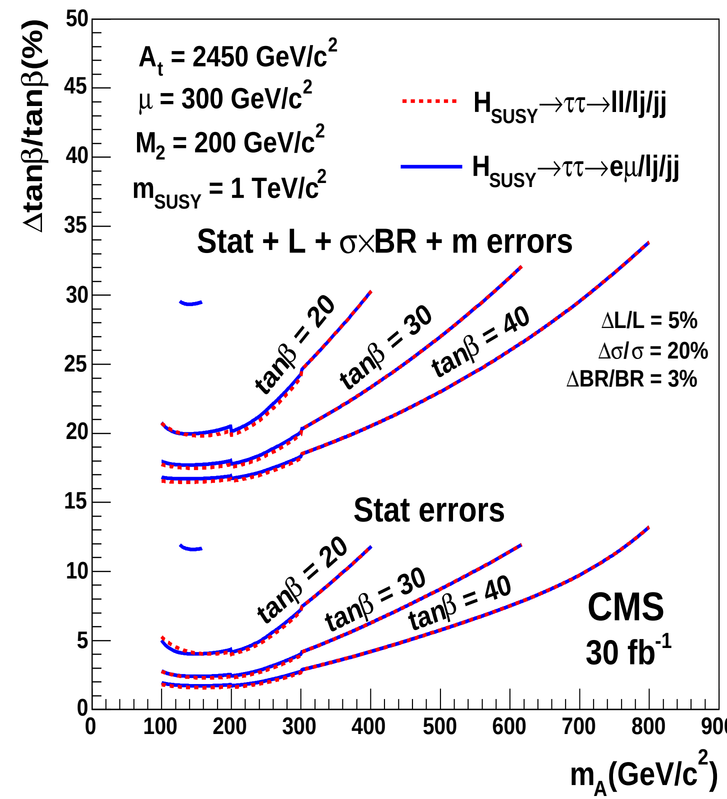


The heavy Higgsses

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

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

H/A separation very difficult



9. SUSY Higgses at the LHC: difficult scenarios in the MSSM

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

- **There is the "bad luck" scenario in which only h is observed:**

– looks SM–like at the 10% level (and $\mathrm{M_{SUSY}} \gtrsim 3$ TeV...): SM

- **There are scenarii where searches are different from standard 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.

– Higgses 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

9. SUSY Higgses at the LHC: the CP–violating MSSM

h, H,A are not CP definite states and $\mathrm{h_1, h_2, h_3}$ are CP–mixed states

The relation for the Higgs masses and couplings different from MSSM.

There is the possibility of a light Higgs which has escaped detection.

An example is the CPX scenario

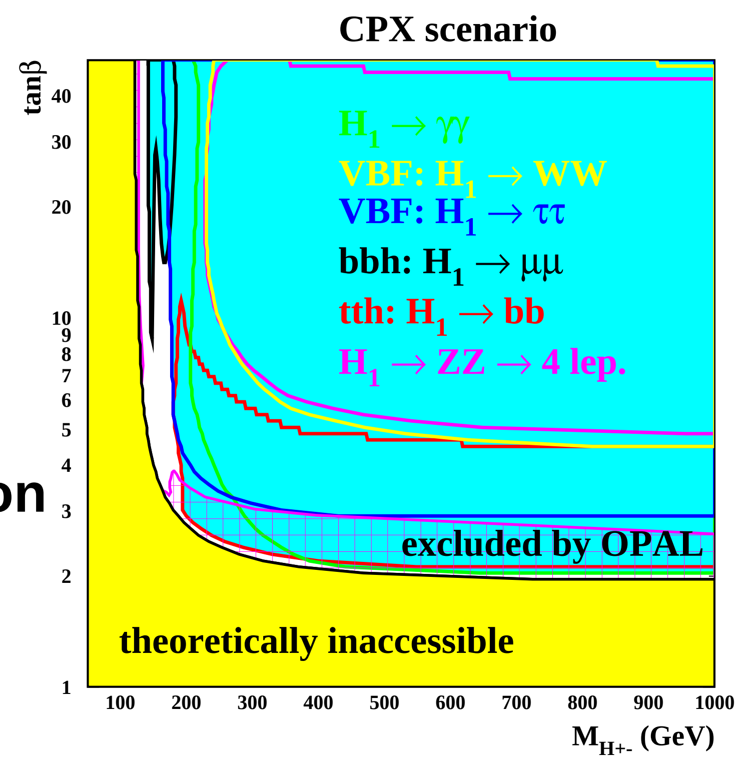
- **$\mathrm{h_1}$ light but weak cplgs to W,Z**
- **$\mathrm{h_2 \to h_1 h_1}$ decays allowed**
- **$\mathrm{h_3}$ couplings to VV reduced...**

All neutral Higgses escape detection:

only (SM-like) $\mathrm{h_2}$ has large cross section

$\mathrm{h_2 \to h_1 h_1 \to 4b, 4\tau}$ unobservable.

Still, one has $\mathrm{t \to H^+ b \to b + hW^*}$



9. SUSY Higgses at the LHC: the NMSSM

In the NMSSM with $h_{1,2,3}, a_{1,2}, h^{\pm}$ one can have Higgs to Higgs decays:

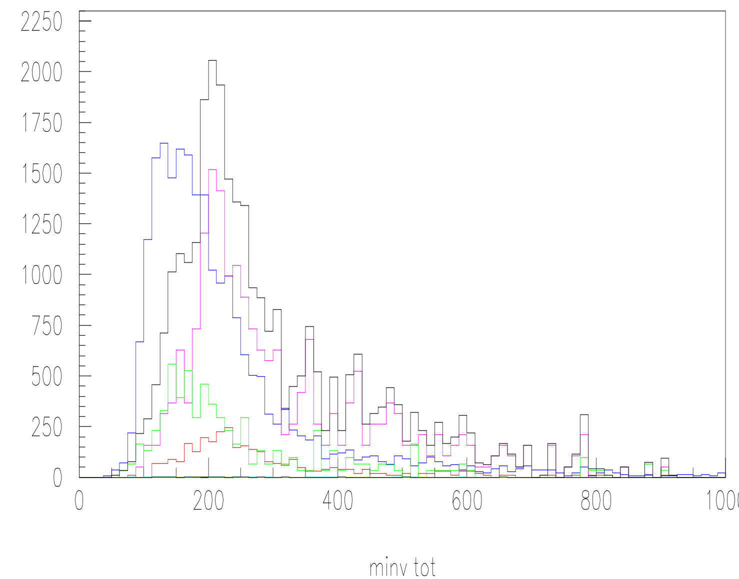
then the possibility of missing all Higgs bosons is not yet ruled out!

Higgs → Higgs+Higgs $\rightarrow 4b, 2b2\tau$

searches very difficult at the LHC:

$$pp \rightarrow qq \rightarrow\rightarrow W^*W^*qq \rightarrow h_1 qq$$

$$h_1 \rightarrow a_1 a_1 \rightarrow b\bar{b}\tau\tau \times 500$$

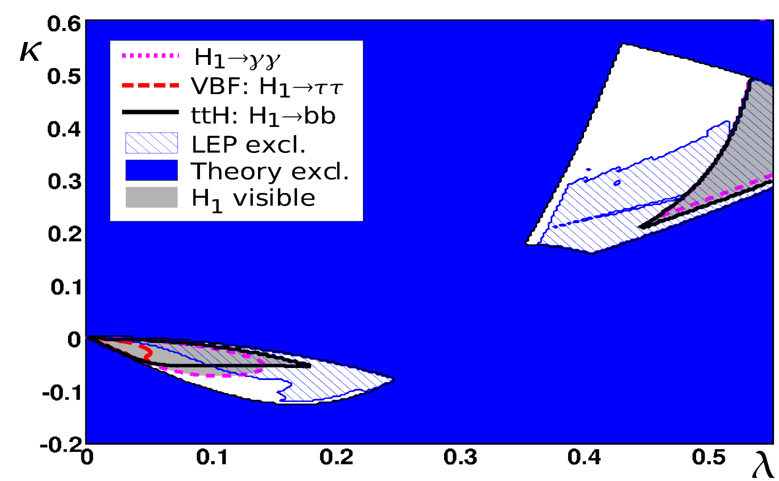


Higgs → Higgs+Higgs $\rightarrow 4\tau \rightarrow 4\ell X$

also difficult but detection possible

using VBF + all h_1 decay channels

(same for all Higgses can be done)



9. SUSY Higgses at the LHC: invisible Higgs?

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

- **In MSSM, Higgs $\to \chi_1^0 \chi_1^0, \tilde{\nu}\tilde{\nu}$, etc.. as already discussed.**
- **In MSSM with $R\!\!\!/_p$: Higgs $\to JJ$ could be dominant.**
- **The SM when minimally extended to contain a singlet scalar field (which decouples from f/V), $H \to SS$ 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: suppressed f/V couplings and Higgs decays to radions**
- **Presence of new quarks which alter production**
- **Composite light Higgs boson**

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

10. Conclusion

The LHC will tell!