Higgs Boson Physics, Part III

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Outline of Part III

- Searching for a Higgs boson: present and future.
- Higgs boson physics at the Tevatron, Run II.

  $\longrightarrow$ Main production modes.
  $\longrightarrow$ Exclusion/discovery reach for a SM/MSSM Higgs boson.

- Higgs boson physics at the Large Hadron Collider (LHC).

  $\longrightarrow$ Main production modes.
  $\longrightarrow$ Discovery reach for a SM/MSSM Higgs boson.
  $\longrightarrow$ Measurements of the Higgs boson mass, width, spin.
  $\longrightarrow$ Measurements of Higgs boson couplings.

- Higgs boson physics at a high energy Linear Collider (LC).

  $\longrightarrow$ Production reach for a SM/MSSM Higgs boson.
  $\longrightarrow$ Precision measurements of most Higgs boson properties.

Some References for Part III

- Theory and Phenomenology of the Higgs boson(s):
  - ▷ Higgs Boson Theory and Phenomenology, M. Carena and H.E. Haber, hep-ph/0208209
- Specific studies and reports:
  - ▷ CMS Collaboration, CERN/LHCC/94-38,1994
  - ▷ ATLAS Collaboration, CERN/LHCC/99-15,1999
  - ▷ Report of the Tevatron Higgs working group, hep-ph/0010338.
  - ▷ Proceedings of the Les Houches Workshop on Physics at TeV Colliders, 2001.
  - ▷ Results of the Tevatron Higgs sensitivity study, October 2003.
  - ▷ Les Houches workshop on Physics at TeV Colliders: report of the Higgs working group, hep-ph/0406152.
  - ▷ TESLA technical design report, Part III, hep-ph/0106315.
  - ▷ Linear Collider Physics Resourche Book, Part II, hep-ex/0106056.

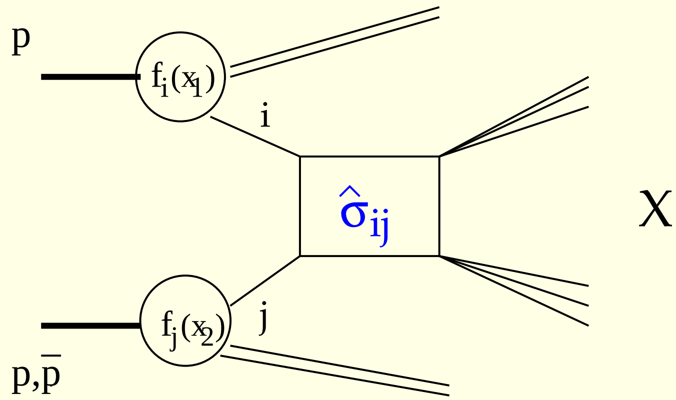
Searching for the Higgs boson: present and future

- ▷ A light Higgs boson, in the 110-180 GeV range, could be discovered during Run II of the Tevatron (Fermilab), with $\sqrt{s} = 1.96$ TeV.

- ▷ The Large Hadron Collider (CERN), with $\sqrt{s} = 14$ TeV, will cover the entire Higgs boson mass range up to 1 Tev, and start measuring mass, couplings, and width of the discovered particle.

- ▷ A high energy LC (?), with $\sqrt{s} \geq 500$ GeV, will unambiguously identify the nature of any discovered new particle, via precision measurements of its mass, spin, couplings, and width.

The basic picture of a $p\bar{p}, pp \rightarrow X$ high energy process ...



where the short and long distance part of the QCD interactions can be factorized and the cross section for $pp, p\bar{p} \rightarrow X$ can be calculated as:

$$\sigma(pp, p\bar{p} \rightarrow X) = \sum_{ij} \int dx_1 dx_2 f_i{}^p(x_1) f_j{}^{p,\bar{p}}(x_2) \hat{\sigma}(ij \rightarrow X)$$

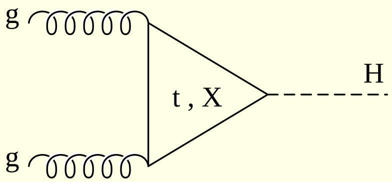
$\longrightarrow$ $ij \rightarrow$ quarks or gluons (partons)

$\longrightarrow$ $f_i^p(x)$, $f_i^{p,\bar{p}}(x)$: Parton Distributions Functions: probability densities (probability of finding parton i in p or $\bar{p}$ with a fraction x of the original hadron momentum)

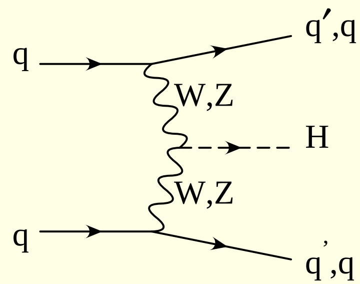
$\longrightarrow$ $\hat{\sigma}(ij \rightarrow X)$: partonic cross section

$p\bar{p}, pp$ colliders: SM Higgs production modes

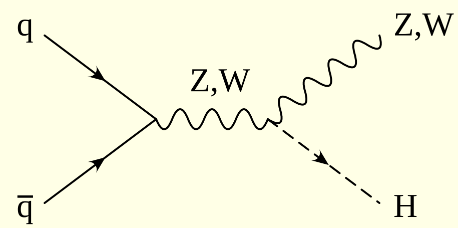
$gg \rightarrow H$



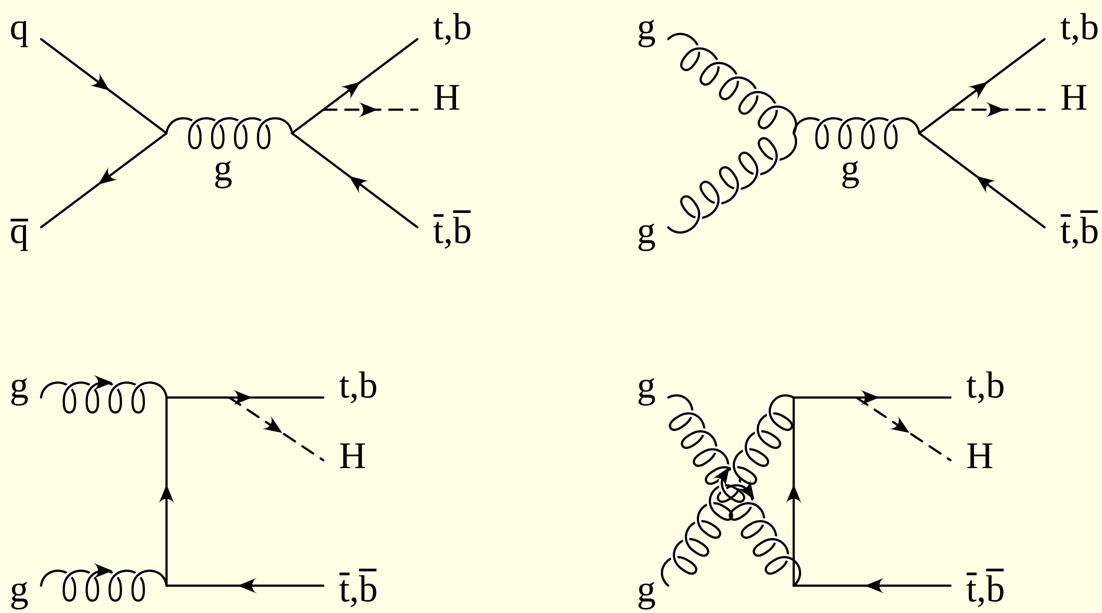
$qq \rightarrow qqH$



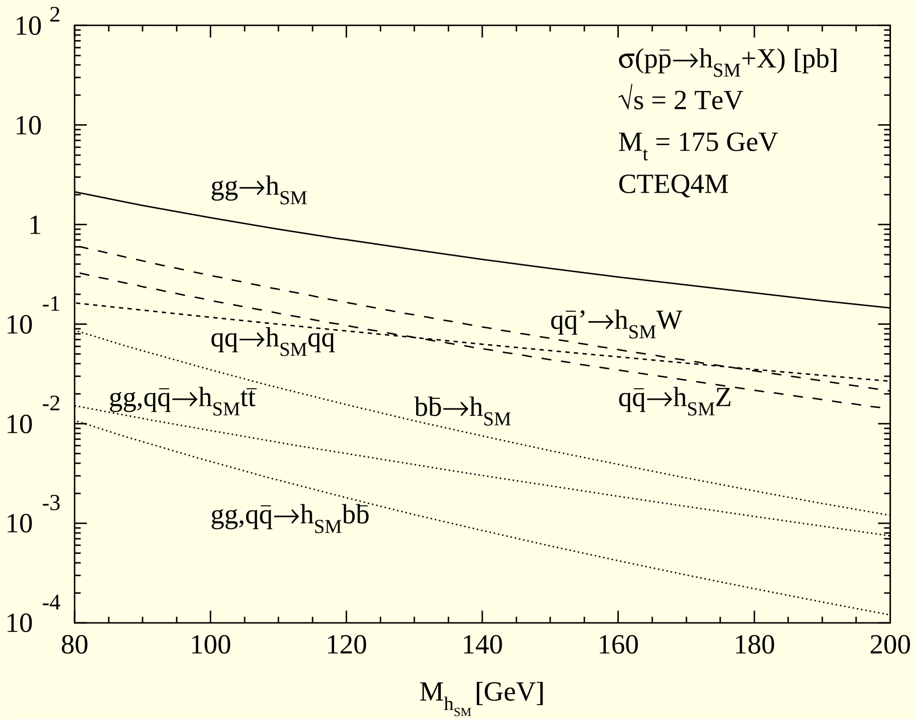
$qq \rightarrow WH, ZH$

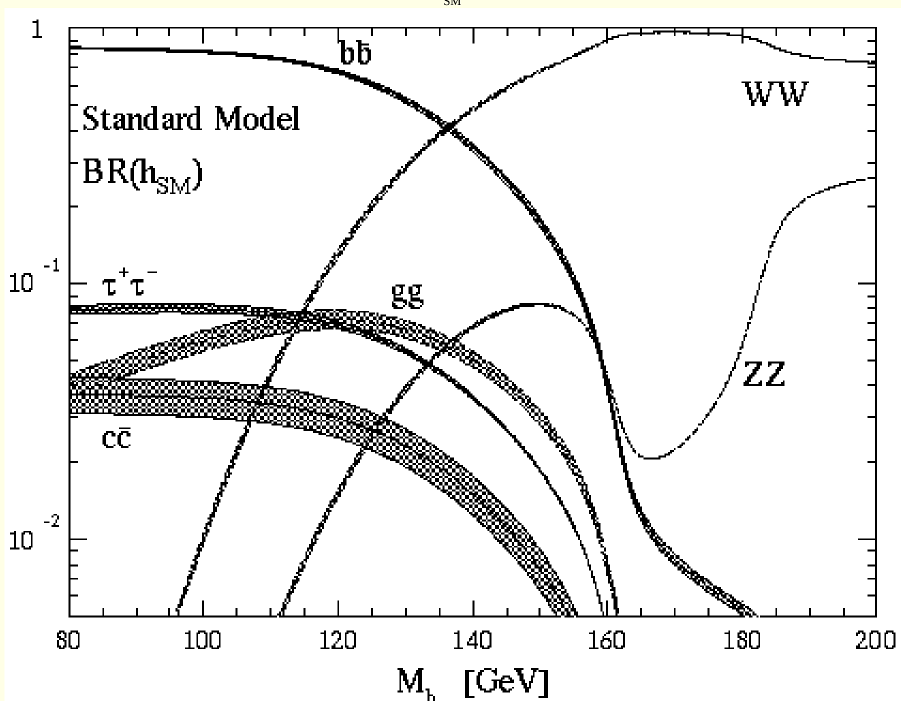


$q\bar{q}, gg \rightarrow t\bar{t}H, b\bar{b}H$



Searching for a SM Higgs boson at the Tevatron





Mainly in:

- Below 130-140 GeV
  $q\bar{q} \to VH,\ H \to b\bar{b}$
- Above 130-140 GeV
  $q\bar{q} \to VH,\ H \to WW$

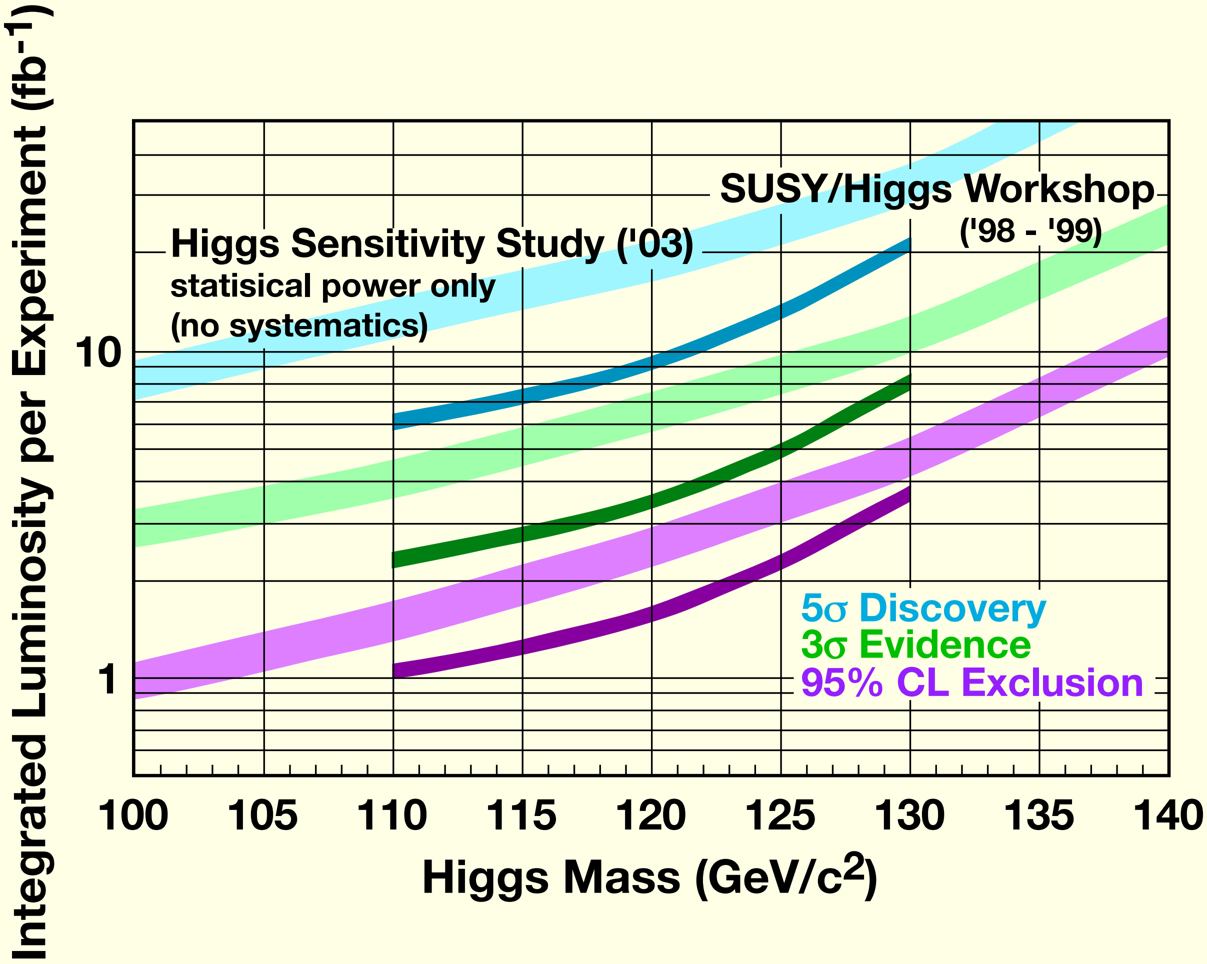
with $V = Z, W$

But also:

- $gg \to H$ (above 130 GeV)
- $q\bar{q} \to t\bar{t}H$ $(H \to b\bar{b}, WW)$

Too low statistics to measure Higgs couplings.

Reach of the Tevatron, Run II, for a SM Higgs boson



Improved studies suggest that less luminosity is needed

both for exclusion and discovery.

Searching for an MSSM Higgs boson at the Tevatron

We expect that:

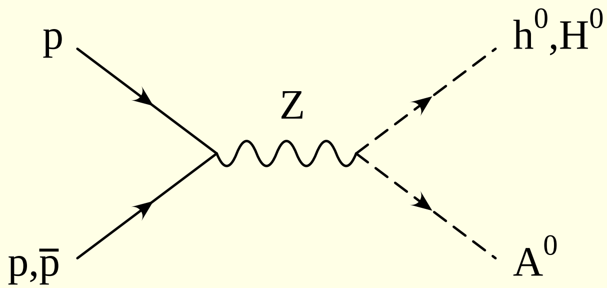
- AVV couplings are absent
- couplings can be enhanced/suppressed
  - ▷ $M_A \gg M_Z$ ($\longrightarrow$ decoupling limit):
    - $\longrightarrow$ $h^0 \longrightarrow H_{SM}$, while
    - $\longrightarrow$ $M_A \simeq M_H$ and $g_{(A,H)b\bar{b}} \gg g_{H_{SM}b\bar{b}}$, $g_{HVV} \ll g_{H_{SM}VV}$.
  - ▷ $M_A \leq M_Z$ and $\tan\beta \gg 1$:
    - $\longrightarrow$ $g_{HVV} \simeq g_{H_{SM}VV}$, while
    - $\longrightarrow$ $M_A \simeq M_h$ and $g_{(A,h)b\bar{b}} \gg g_{H_{SM}b\bar{b}}$, $g_{hVV} \ll g_{H_{SM}VV}$.

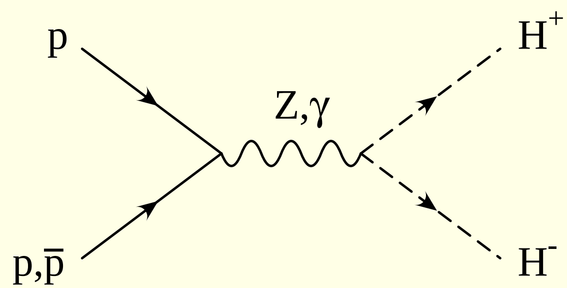
We could also have:

- Higgs bosons decaying into supersymmetric particles.
- Higgs bosons produced in the decay of supersymmetric particles.

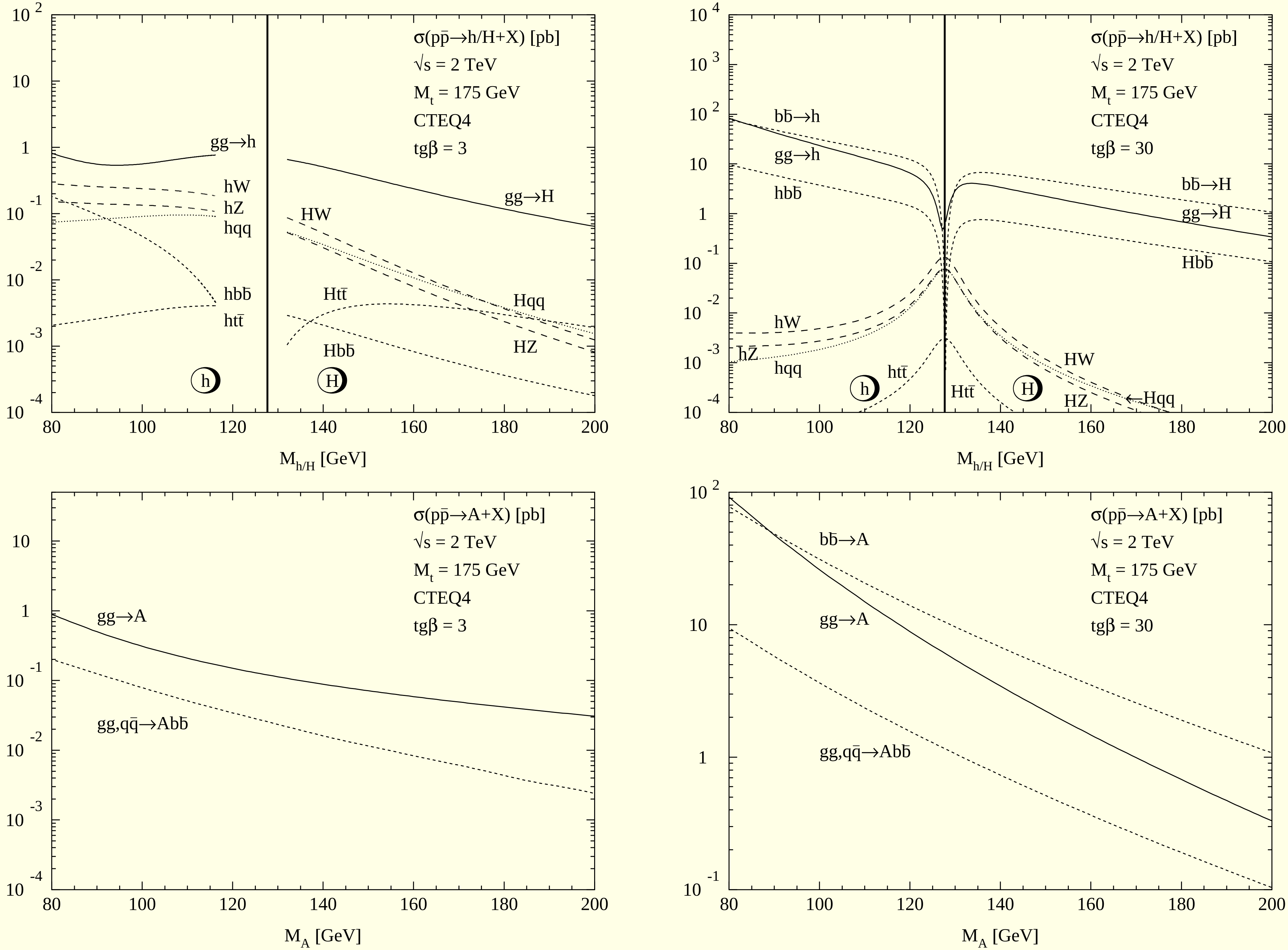
We will consider only:

- SM-like production modes (see previous section)
- the associated production modes:

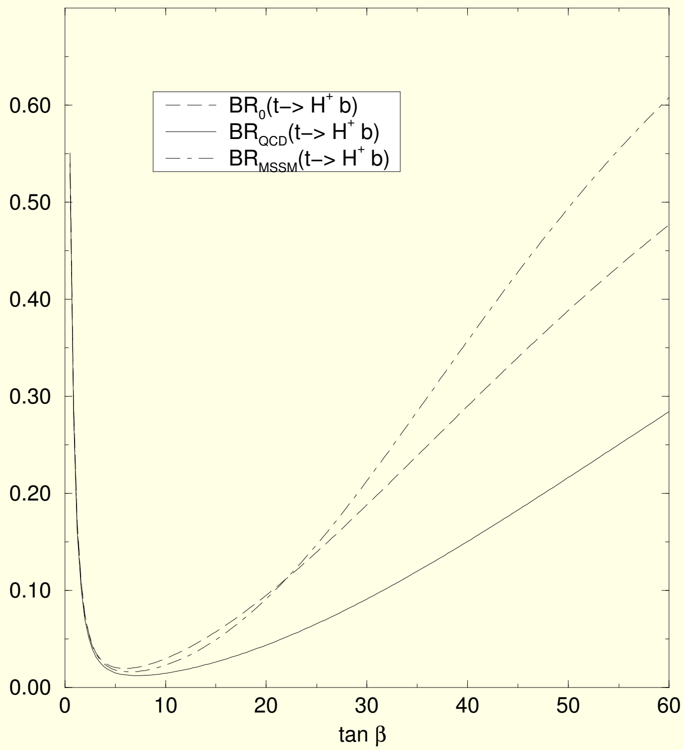




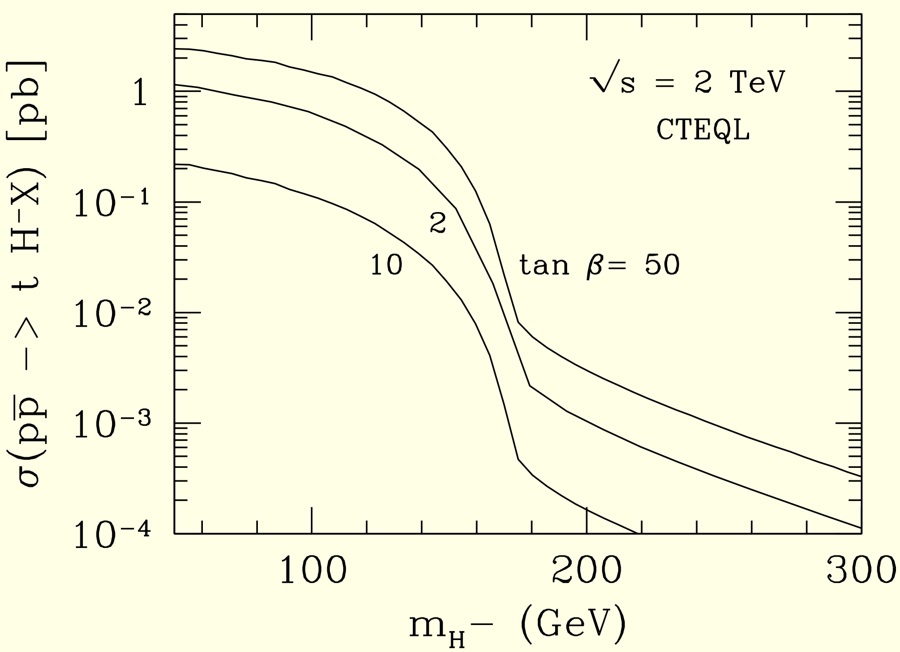
Neutral Higgs boson production cross sections at the Tevatron

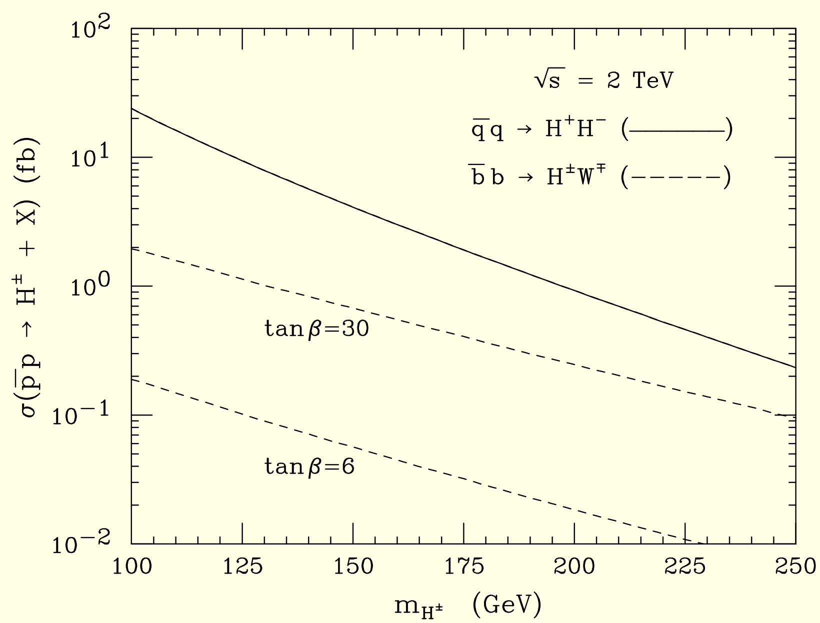


$H^{\pm}$ production at the Tevatron

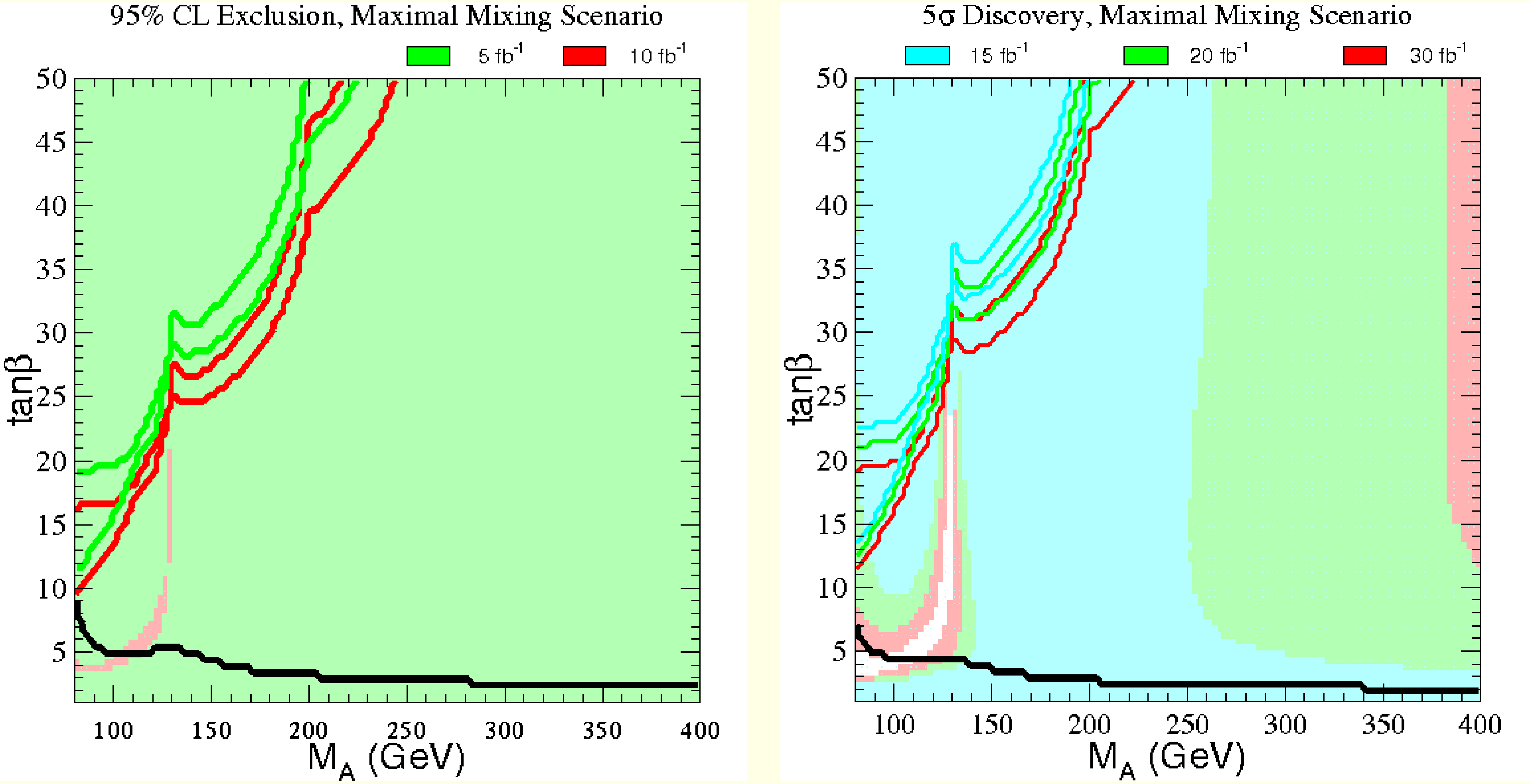


- ▷ $\boxed{M_{H^\pm} < m_t - m_b}$:
  - $\longrightarrow$ $p\bar{p} \to t\bar{t} + t \to bH^+ \; (\bar{t} \to \bar{b}H^-)$
  - $\longrightarrow$ $p\bar{p} \to \bar{t}bH^+, t\bar{b}H^-$
- ▷ $\boxed{M_{H^\pm} > m_t - m_b}$:
  - $\longrightarrow$ $p\bar{p} \to \bar{t}bH^+, t\bar{b}H^-$
  - $\longrightarrow$ $p\bar{p} \to W^\pm H^\mp$
  - $\longrightarrow$ $p\bar{p} \to H^+H^-$





Reach of the Tevatron, Run II, in the MSSM parameter space

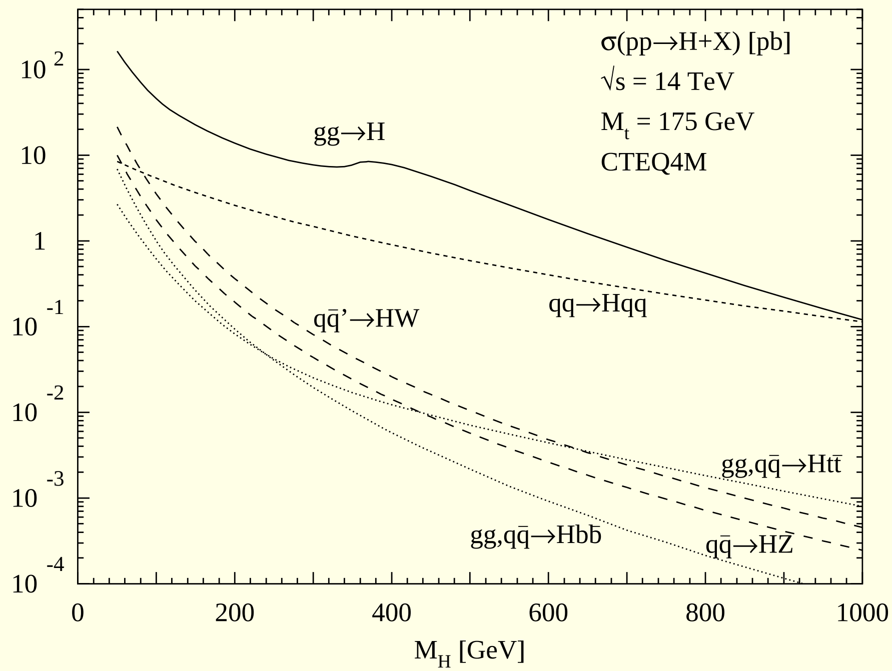


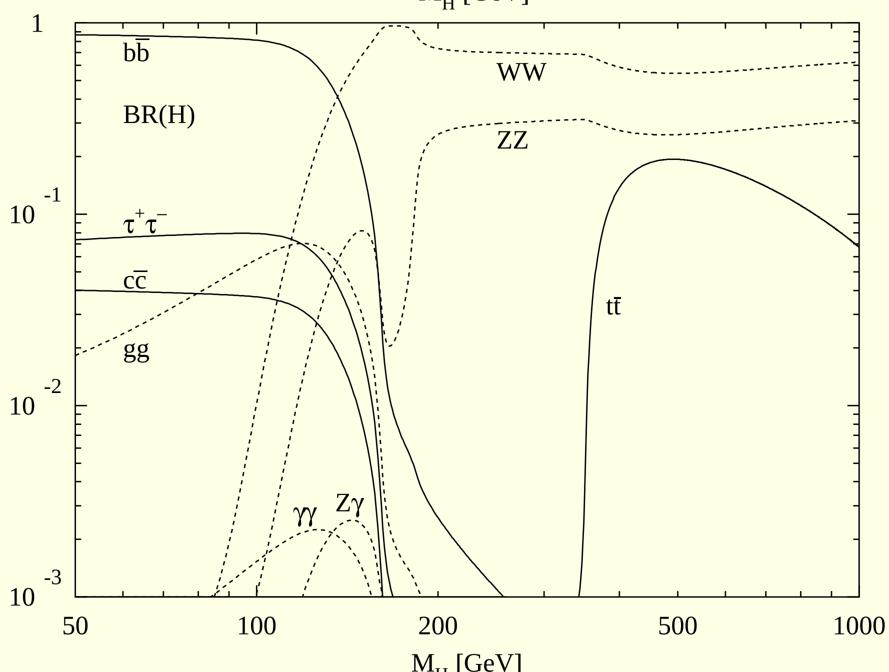
Using:

$\longrightarrow$ $p\bar{p} \to V\phi \;\; (\phi = h^0, H^0)$

$\longrightarrow$ $p\bar{p} \to b\bar{b}\phi \;\; (\phi = h^0, H^0, A^0)$

Searching for a SM Higgs boson at the LHC





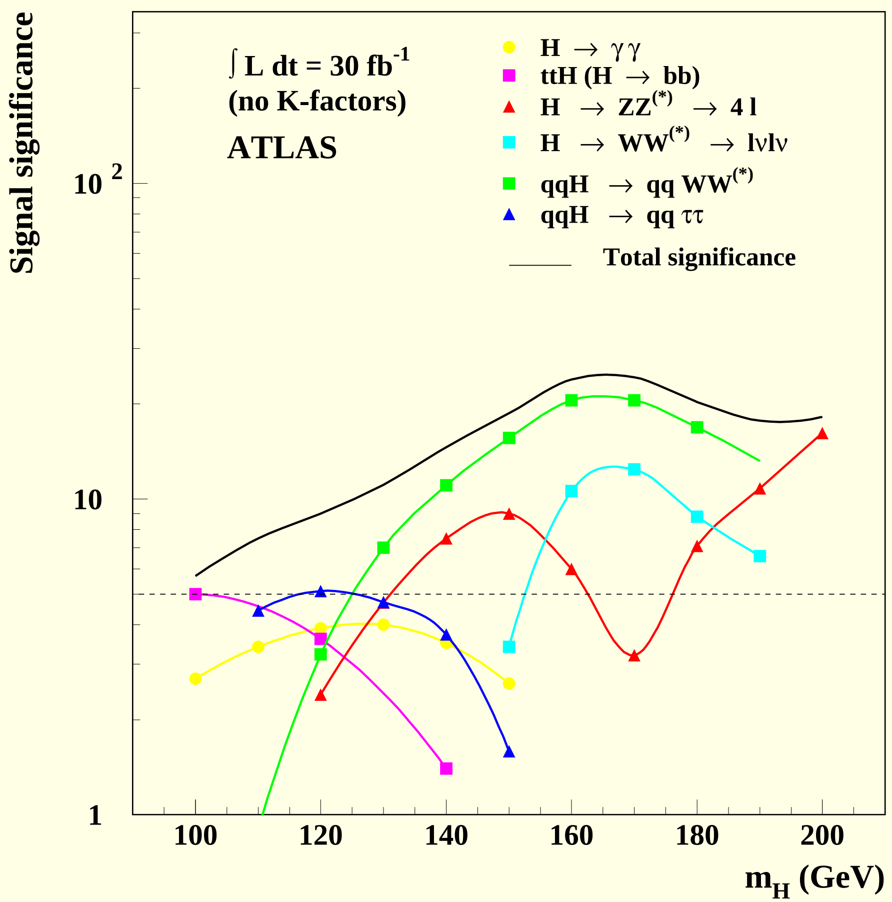
Below 130-140 GeV:

- $gg \to H$, $H \to \gamma\gamma, W^+W^-, ZZ$
- $qq \to qqH$, $H \to \gamma\gamma, W^+W^-, ZZ, \tau^+\tau^-$
- $q\bar{q}, gg \to t\bar{t}H$, $H \to b\bar{b}, \tau^+\tau^-$

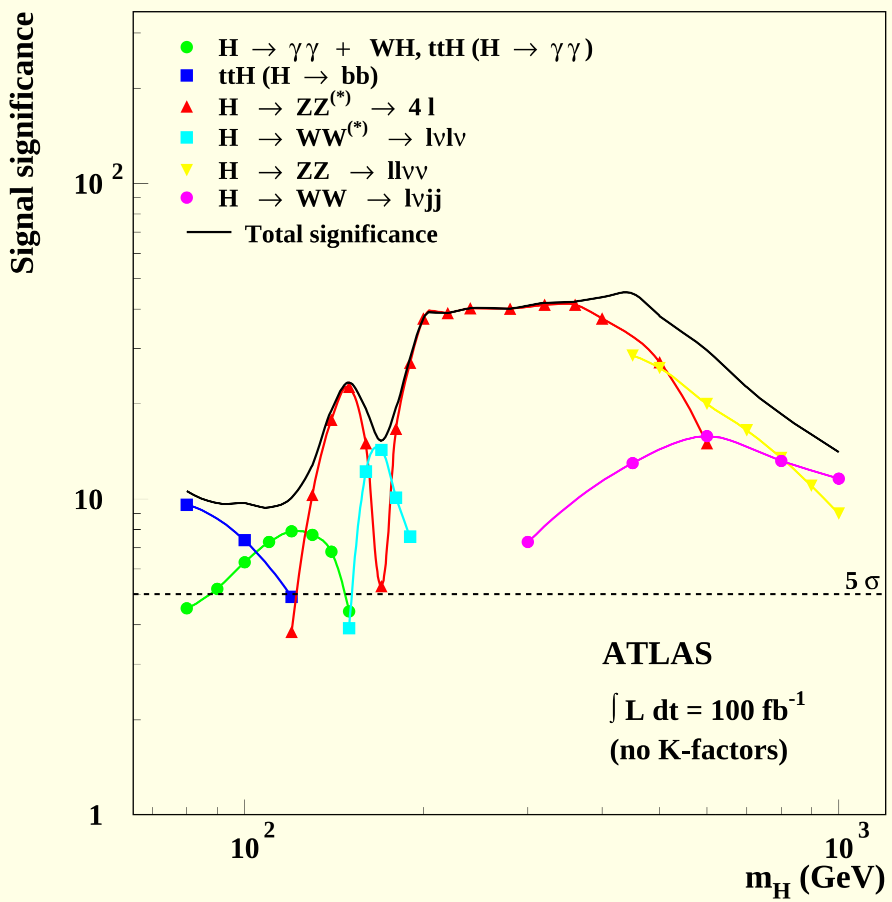
Above 130-140 GeV:

- $gg \to H$, $H \to W^+W^-, ZZ$
- $qq \to qqH$, $H \to \gamma\gamma, W^+W^-, ZZ$
- $q\bar{q}, gg \to t\bar{t}H$, $H \to W^+W^-$

Discovery reach of the LHC for a SM Higgs boson



Low luminosity

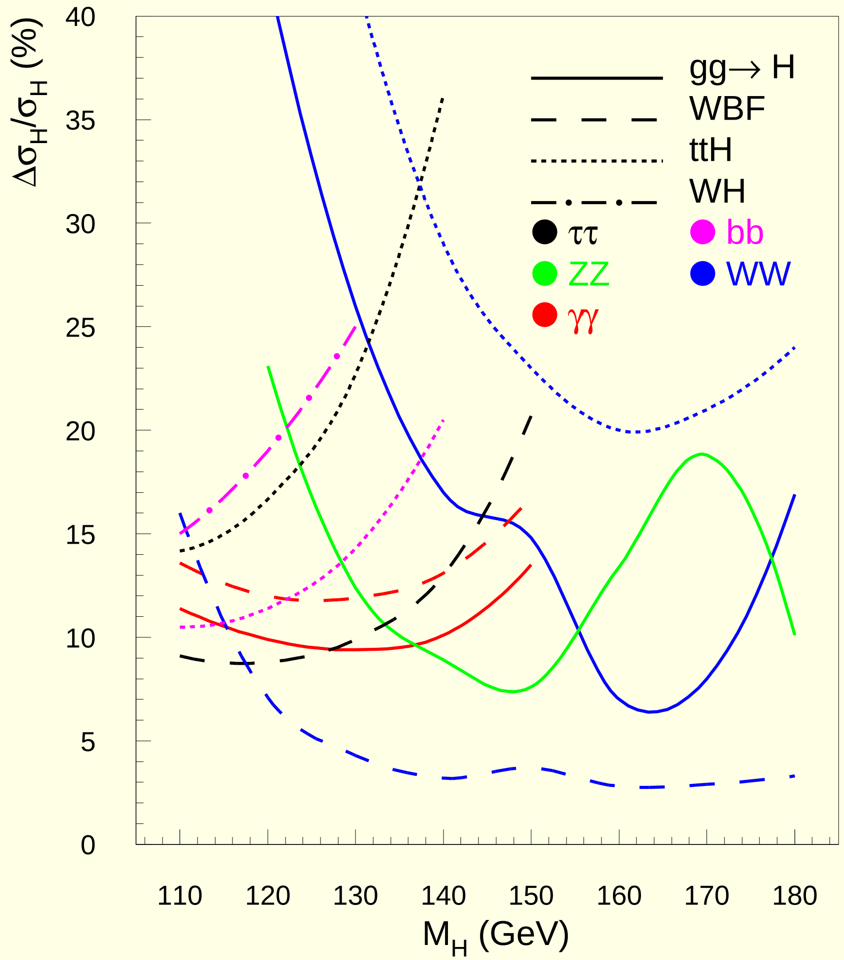


High luminosity

Mass, Width, Spin and more

- Color and charge are given by the measurement of a given (production+decay) channel.
- The Higgs boson mass will be measured with 0.1% accuracy in $H \to ZZ^* \to 4l^\pm$, complemented by $H \to \gamma\gamma$ in the low mass region. Above $M_H \simeq 400$ GeV precision deteriorates to $\simeq 1\%$ (lower rates).
- The Higgs boson width can be measured in $H \to ZZ^* \to 4l^\pm$ above $M_H \simeq 200$ GeV. The best accuracy of $\simeq 5\%$ is reached for $M_H \simeq 400$ GeV. Below $M_H \simeq 200$ GeV $\longrightarrow$ see later.
- The Higgs boson spin could be measured through angular correlations between fermions in $H \to VV \to 4f$, but this will be impaired by lack of statistics.

The LHC can also measure most SM Higgs couplings at 10-30%!



Consider all accessible channels:

- Below 130-140 GeV

  $gg \to H \; , \; H \to \gamma\gamma, WW, ZZ$

  $qq \to qqH \; , \; H \to \gamma\gamma, WW, ZZ, \tau\tau$

  $q\bar{q}, gg \to t\bar{t}H \; , \; H \to b\bar{b}, \tau\tau$

- Above 130-140 GeV

  $gg \to H \; , \; H \to WW, ZZ$

  $qq \to qqH \; , \; H \to \gamma\gamma, WW, ZZ$

  $q\bar{q}, gg \to t\bar{t}H \; , \; H \to WW$

Observing a given production+decay (p+d) channel gives a relation:

$$(\sigma_p(H)\mathrm{Br}(H \to dd))^{exp} = \frac{\sigma_p^{th}(H)}{\Gamma_p^{th}} \frac{\Gamma_d \Gamma_p}{\Gamma}$$

(in the narrow Higgs approximation).

Associate to each channel $(\sigma_p(H) \times Br(H \to dd))$

$$Z_d^{(p)} = \frac{\Gamma_p \Gamma_d}{\Gamma} \qquad \begin{cases} \Gamma_p \simeq g_{Hpp}^2 = y_p^2 \to \text{production} \\ \Gamma_d \simeq g_{Hdd}^2 = y_d^2 \to \text{decay} \end{cases}$$

From LHC measurements, given the current simulated accuracies:

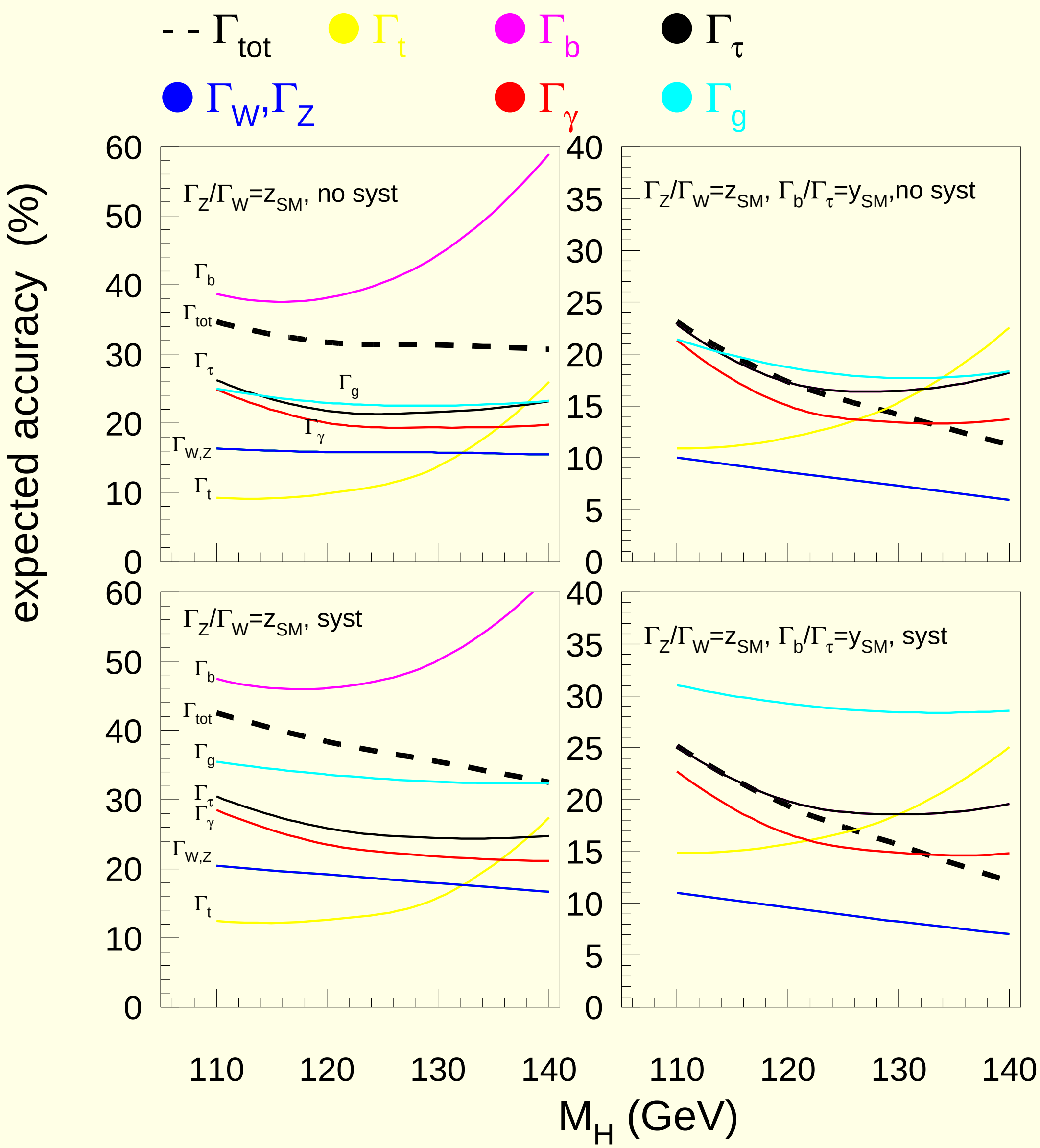
- Determine in a model independent way ratios of couplings at the $10-20\%$ level, for example:

$$\frac{y_b}{y_\tau} \quad \longleftarrow \quad \frac{\Gamma_b}{\Gamma_\tau} = \frac{Z_b^{(t)}}{Z_\tau^{(t)}}$$

$$\frac{y_t}{y_g} \quad \longleftarrow \quad \frac{\Gamma_t}{\Gamma_g} = \frac{Z_\tau^{(t)} Z_\gamma^{(w)}}{Z_\tau^{(w)} Z_\gamma^{(g)}}$$

- Determine individual couplings at the 10-30% level (under the assumption: $\Gamma = \Gamma_b + \Gamma_\tau + \Gamma_w + \Gamma_z + \Gamma_g + \Gamma_\gamma$)

Accuracies on Couplings and Width of a Higgs boson with $M_H < 140$ GeV



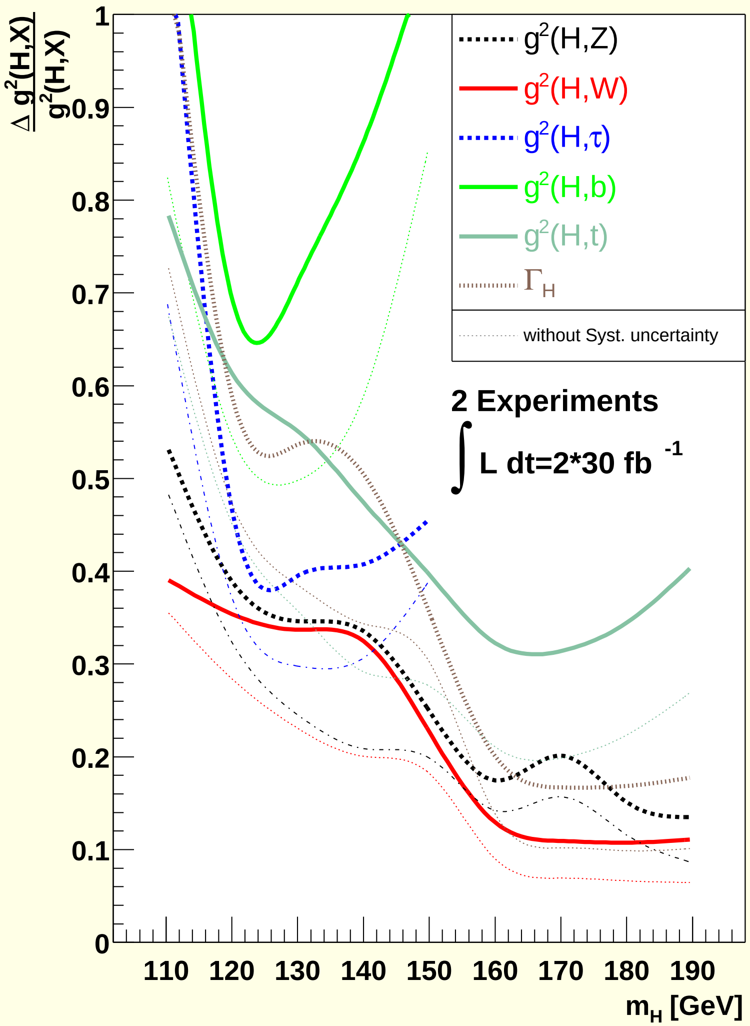
systematics:

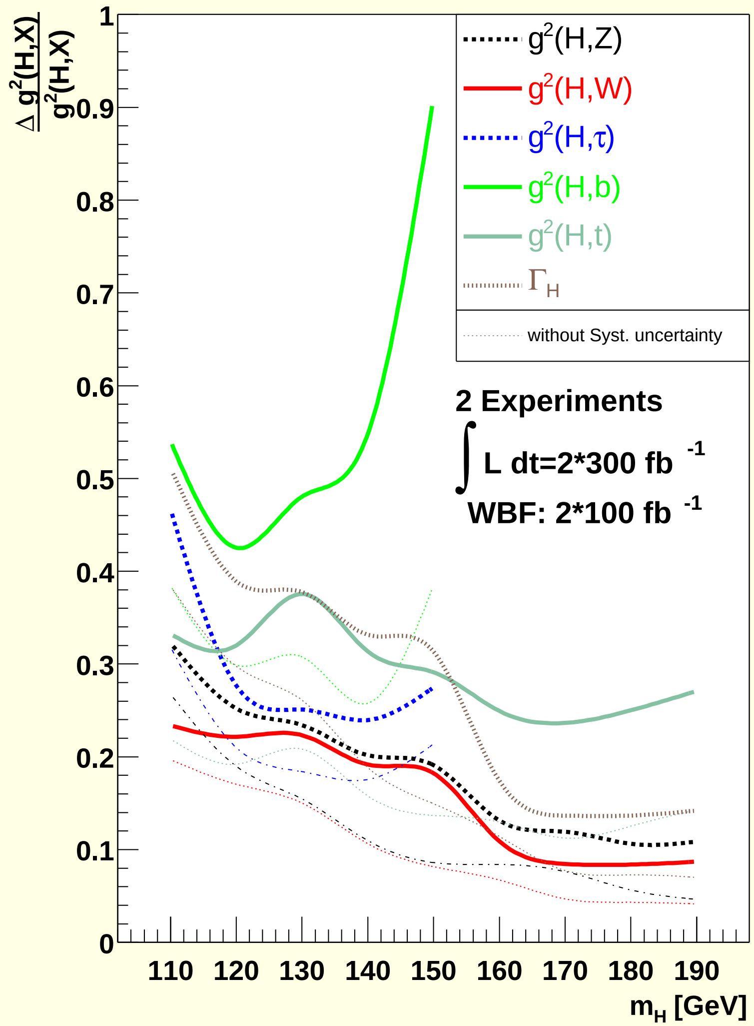
theoretical error on

$$\left\{ \begin{array}{l} gg \to H \longrightarrow 20\% \\ qq \to qqH \longrightarrow 5\% \\ pp \to t\bar{t}H \longrightarrow 10\% \end{array} \right.$$

Plus assumptions on Γ_Z/Γ_W (and Γ_τ/Γ_b)

Toward a more model independent determination of Higgs couplings and width

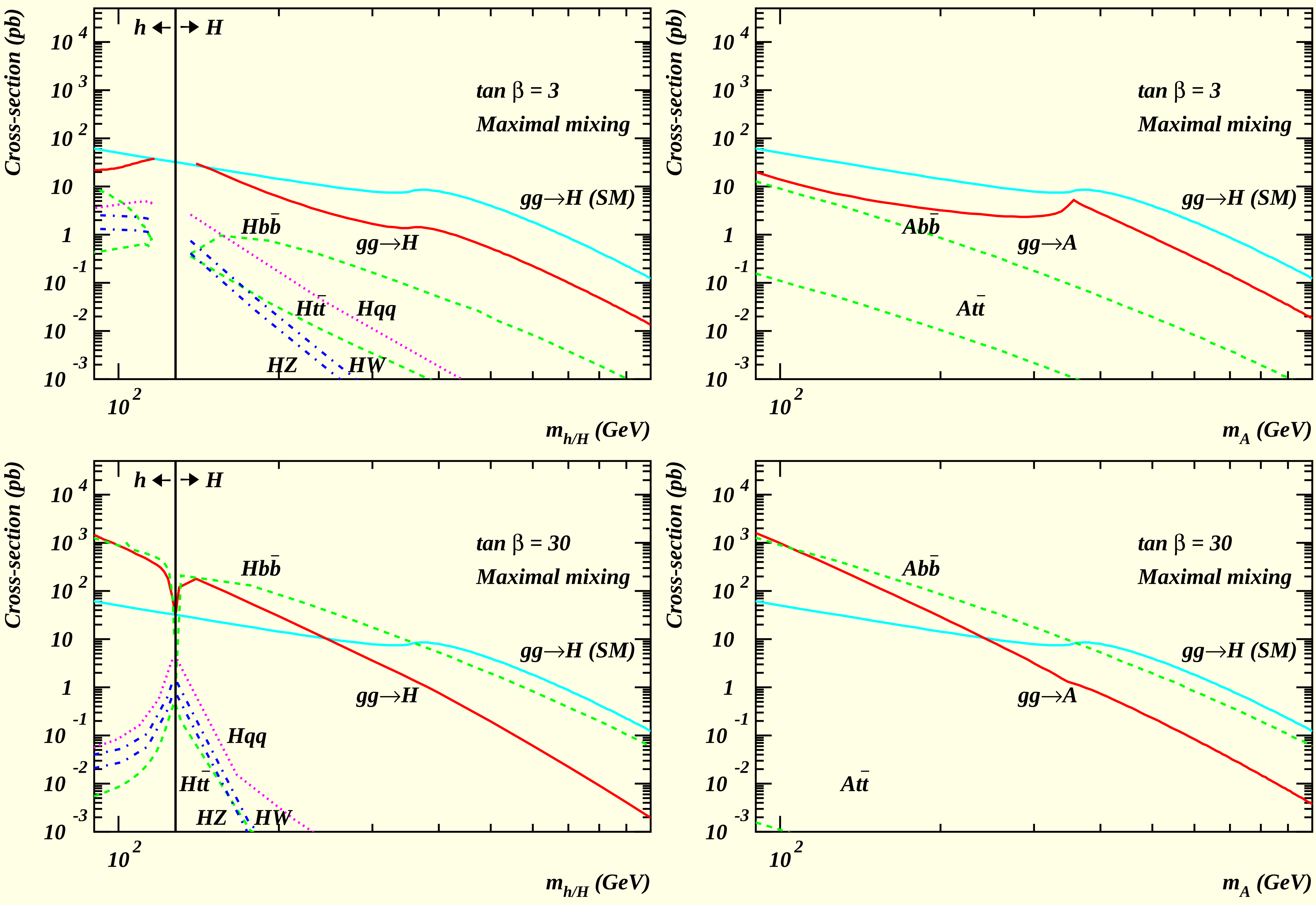




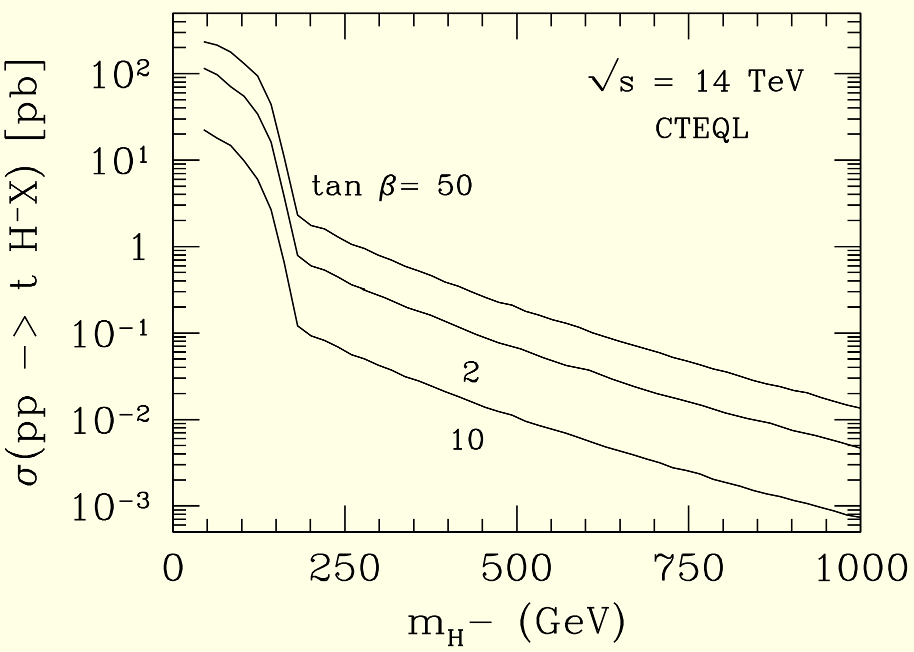
Global χ^2 fit assuming

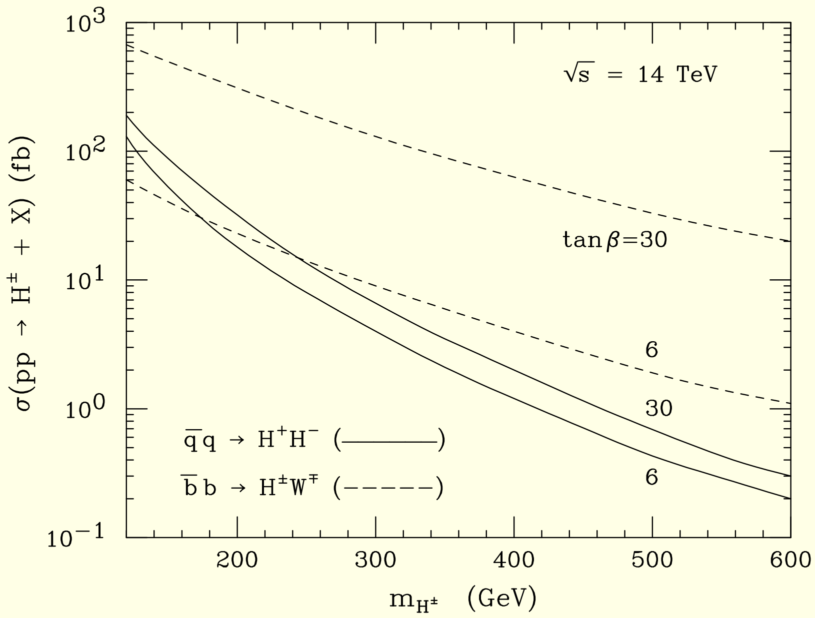
- $\longrightarrow$ $g^2(H,V) < g^2(H,V,SM) + 5\%$ $(V = W,Z)$
- $\longrightarrow$ new particles in loop production/decay modes
- $\longrightarrow$ unobservable decay modes

MSSM Higgs boson production cross sections at the LHC



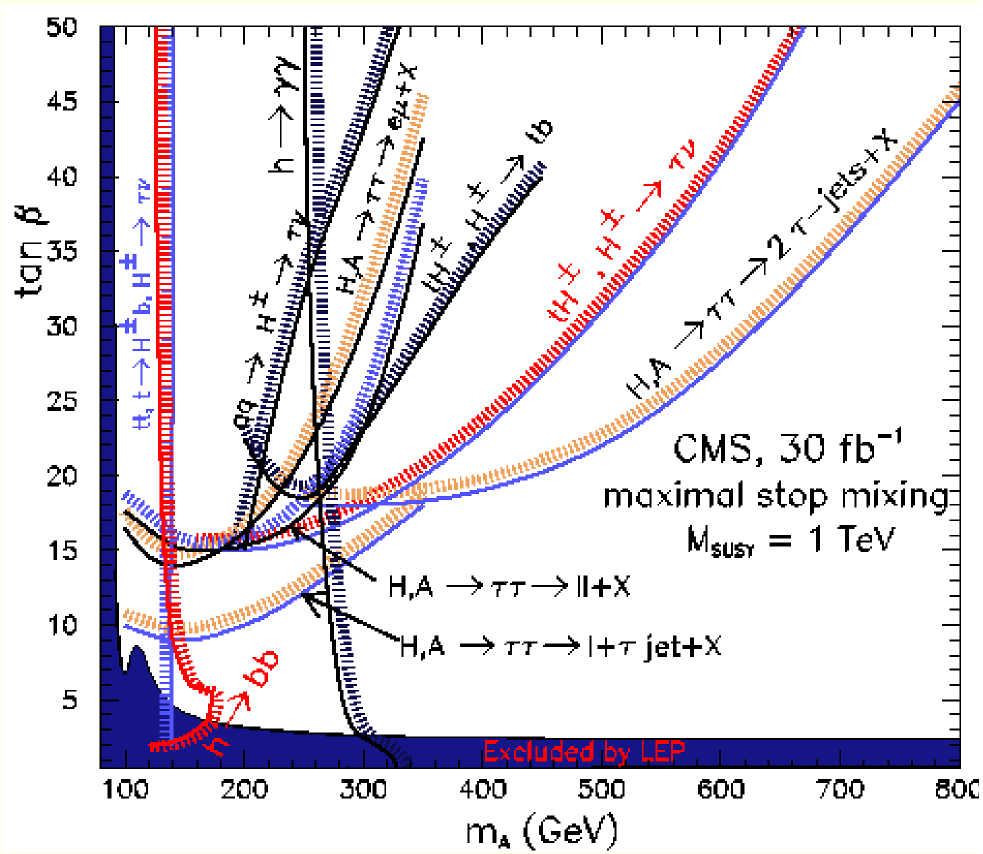
$H^{\pm}$ production at the LHC



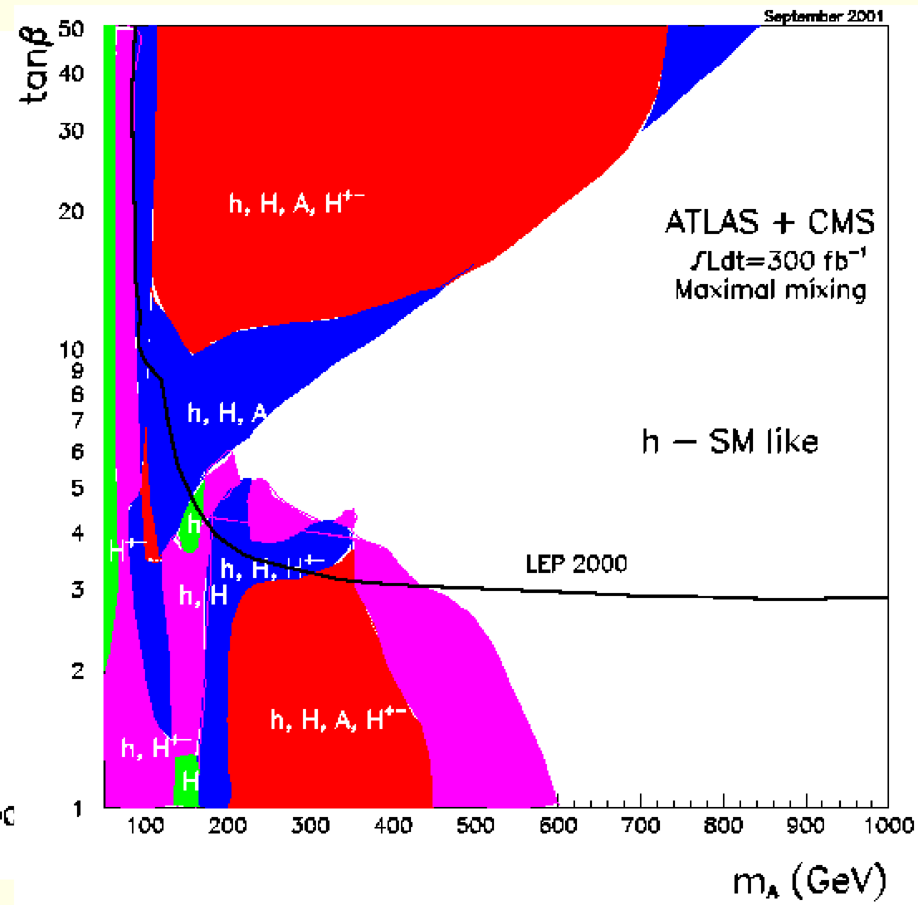


(see Tevatron section for more details on production modes)

Reach of the LHC in the MSSM parameter space

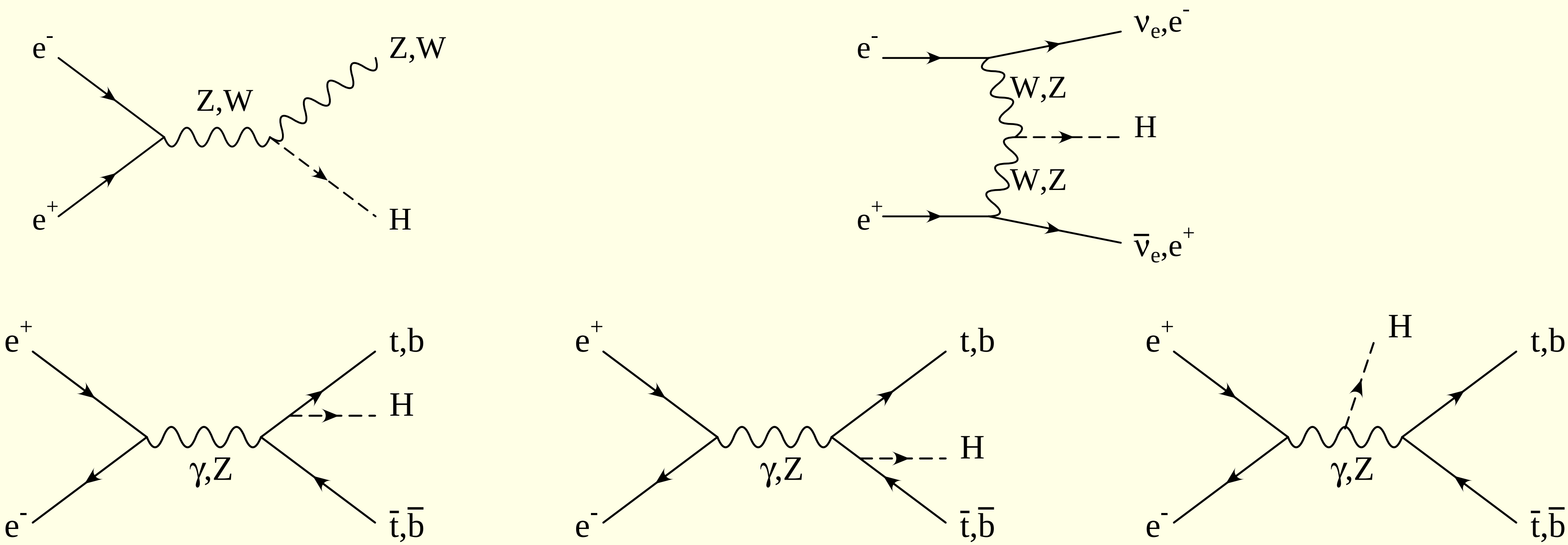


Low luminosity, CMS only

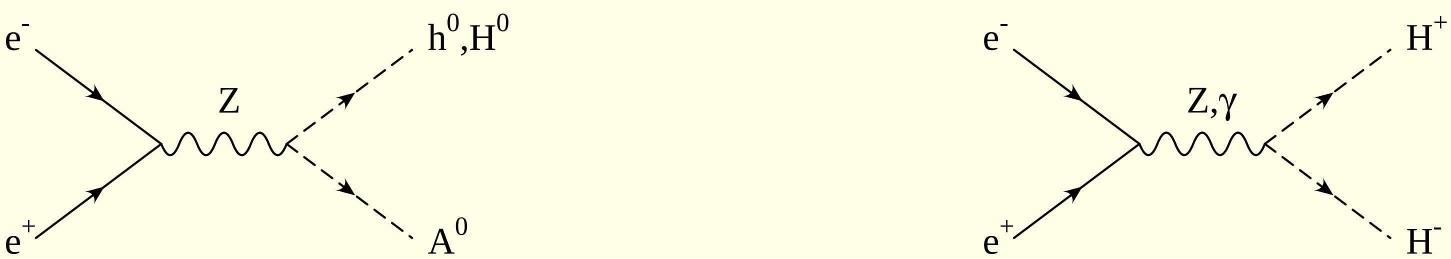


High luminosity, ATLAS+CMS

e^+e^- colliders: SM Higgs production modes

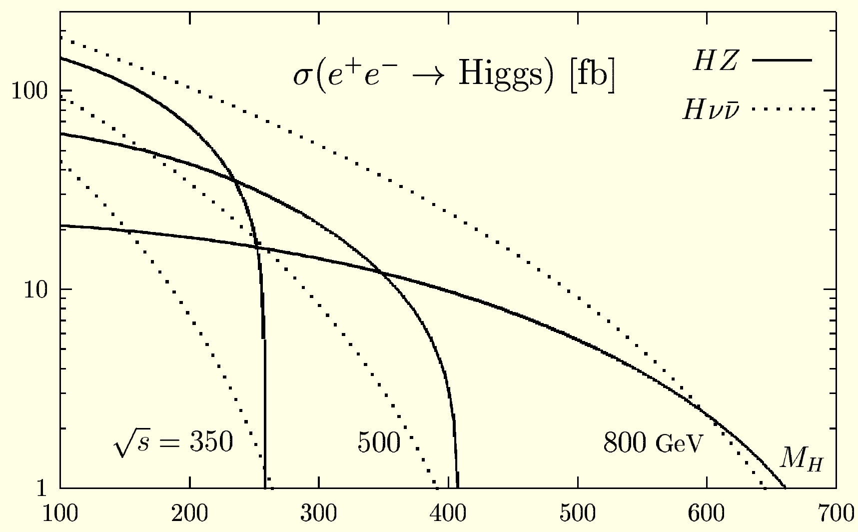


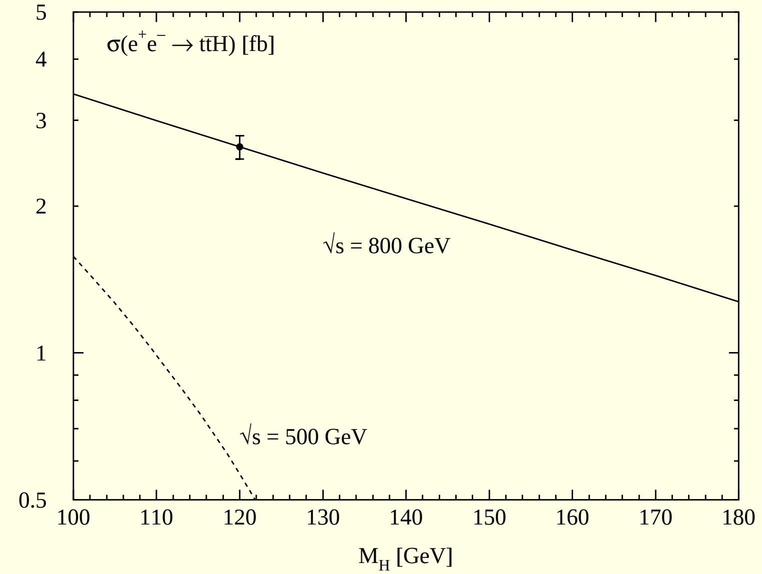
and additional MSSM modes



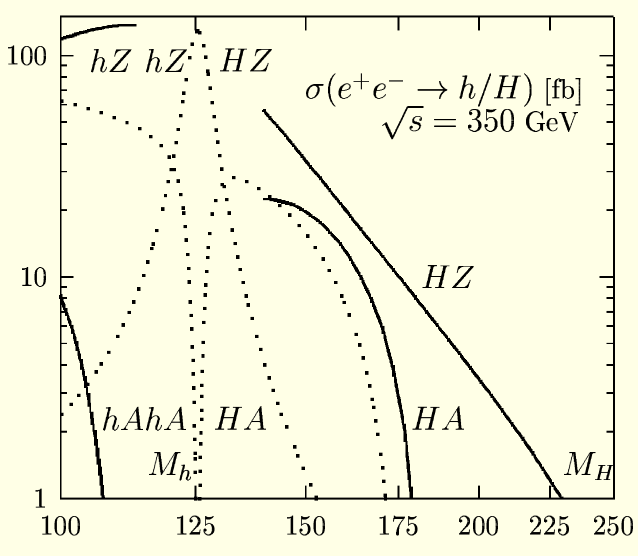
The Linear Collider: precision Higgs physics

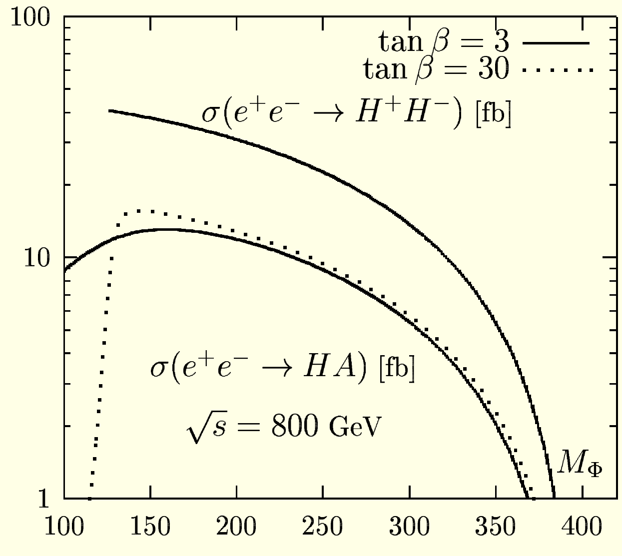
Production cross sections for a SM Higgs boson:





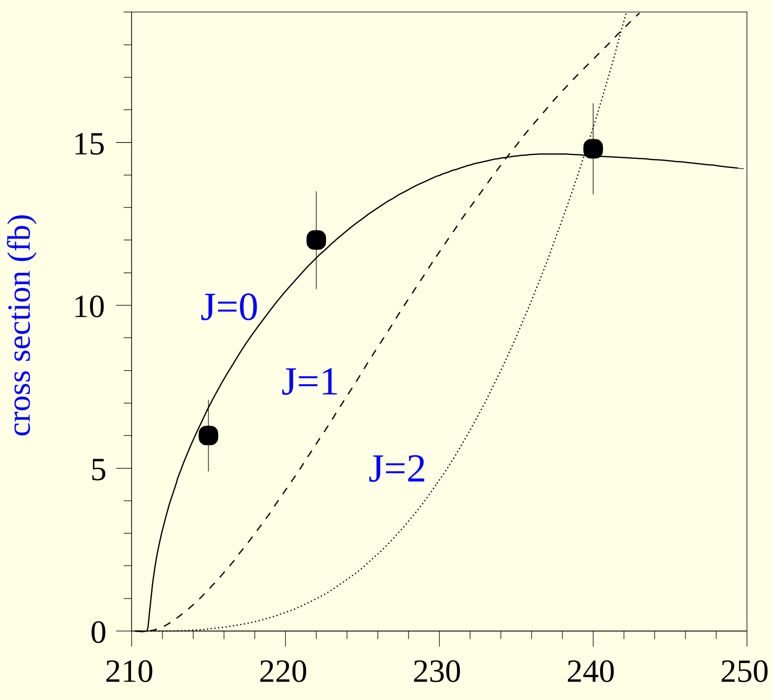
Production cross sections for an MSSM Higgs boson:





Program:

One or more Higgs bosons will be observed over the entire mass spectrum. A high energy e^+e^- collider will then have the unique possibility of:

- Measure $\sigma(e^+e^- \rightarrow ZH)$ at the 2% level: extract $\mathrm{Br}(H \rightarrow xx)$ in model independent way!
- Measure M_H from the recoiling $f\bar{f}$ mass in $ZH \rightarrow Hf\bar{f}$. Accuracies of the order of 50-80 MeV can be obtained.
- 

spin measured by:

▷ onset slope of the $e^+e^- \rightarrow ZH$

▷ correlations in $e^+e^- \rightarrow ZH \rightarrow 4f, \ldots$

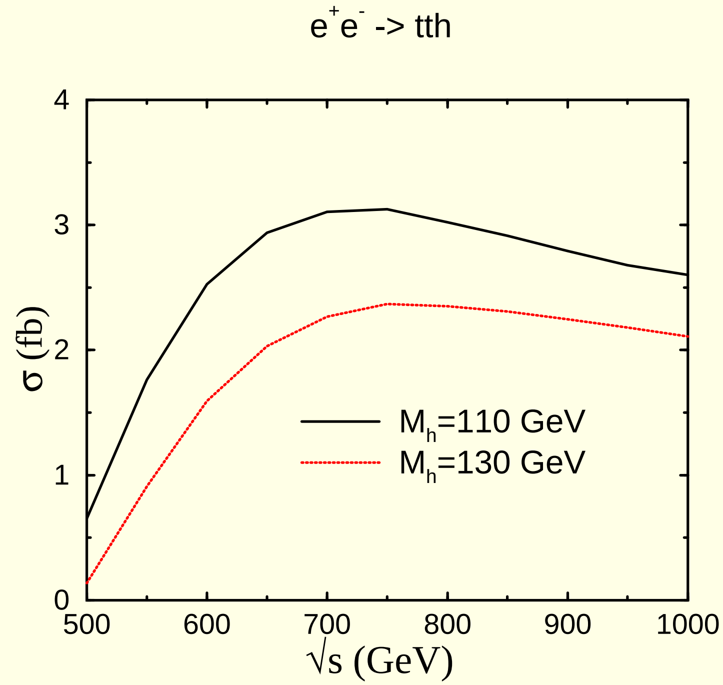
▷ phase space distributions in $e^+e^- \rightarrow t\bar{t}H$

- Measure Γ_H below $M_H \simeq 200$ Gev combining $\mathrm{Br}(H \to W^+W^-)$ (from $e^+e^- \to ZH$) and g_{HWW} (from $e^+e^- \to H\nu\bar{\nu}$), with a $\simeq 6\%$ accuracy.

Ex.: SM Higgs boson, $\sqrt{s} = 120$ GeV

Coupling:	$Hb\bar{b}$	$H\tau^+\tau^-$	$Hc\bar{c}$	HWW	HZZ	$Ht\bar{t}$	HHH
($M_H = 120$ GeV)	2.2%	3.3%	3.7%	1.2%	1.2%	25%	17%
($M_H = 140$ GeV)	2.2%	4.8%	10%	2.0%	1.3%		23%
Theory	1.4%	2.3%	23%	2.3%	2.3%	5%	

Difficult measurements:



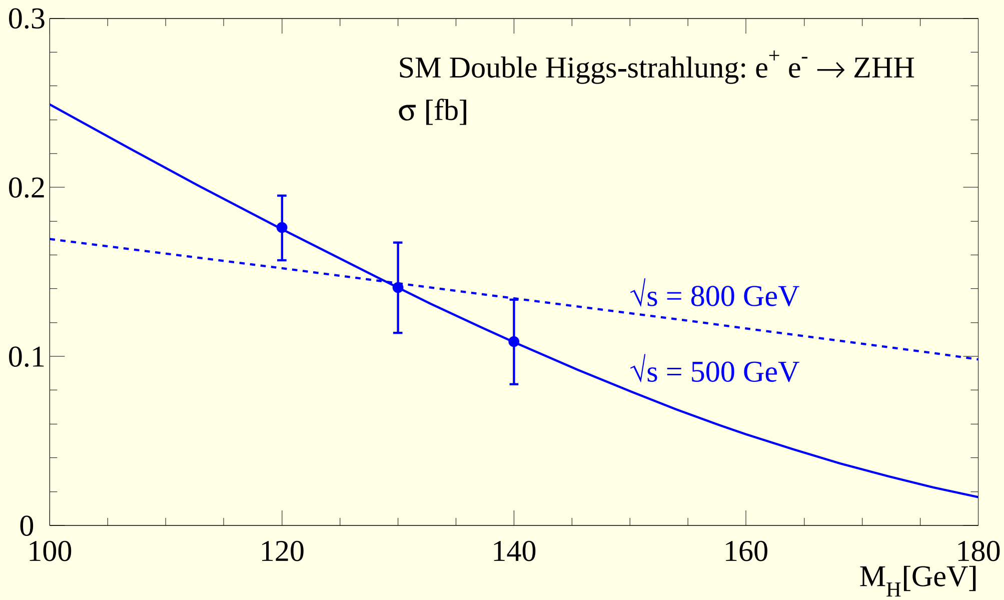
Top quark Yukawa coupling:

Optimal scale $\sqrt{s} \simeq 700 - 800$ GeV:

$\longrightarrow \sqrt{s} = 800$ GeV: $\frac{\delta g_{tth}}{g_{tth}} \simeq 5.5\%$

$\longrightarrow \sqrt{s} = 500$ GeV: $\frac{\delta g_{tth}}{g_{tth}} \simeq 25\%$

$\longrightarrow$ Can the LHC complement it?



Higgs boson self-coupling

$\longrightarrow$ need to wait for CLIC?

Optimal to distinguish H_{SM} from h^0