Higgs boson production at present and future colliders

Laura Reina

CTEQ Summer School, June 2002

- Electroweak Symmetry breaking
- Properties of SM and MSSM Higgs bosons
- Higgs production at past, present and future colliders
  - $\longrightarrow$ LEP: our current knowledge
  - $\longrightarrow$ Tevatron and LHC: present and future
  - $\longrightarrow$ High energy LC: far future

with emphasis on

- ▷ Motivations for precision Higgs studies
- ▷ Impact of QCD corrections
- ▷ Main theoretical uncertainties

The story begins in 1964 ...

with Englert and Brout, Higgs, and Hagen, Guralnik and Kibble

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

The SM Higgs boson:

Spontaneously Breaking the EW Symmetry

Introduce a complex scalar $SU(2)$ doublet:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

with Lagrangian:

$$\mathcal{L}_{\text{scalar}} = (\mathcal{D}^\mu \phi)^\dagger (\mathcal{D}_\mu \phi) - V(\phi)$$

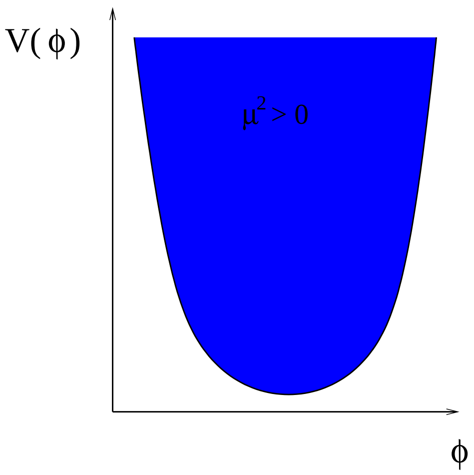
where

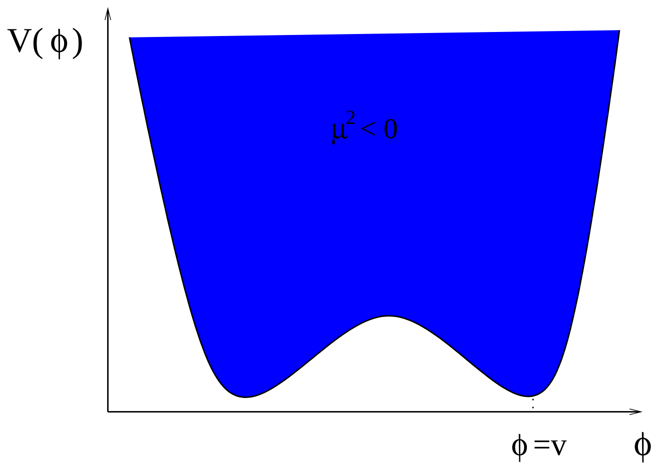
$$\mathcal{D}_\mu = \partial_\mu + i\frac{g'}{2}\mathcal{B}_\mu + i\frac{g}{2}\vec{\tau}\cdot\vec{W}_\mu$$

and

$$V(\phi) = \mu^2(\phi^\dagger\phi) + |\lambda|(\phi^\dagger\phi)^2$$

If $\mu^2 < 0$: Spontaneous Symmetry Breaking





(one dimension)

Minimum energy or vacuum state:

$$\langle\phi\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \quad \text{where} \quad v = \sqrt{\frac{-\mu^2}{|\lambda|}}$$

Convenient parameterization:

$$\phi = \exp\left(i\frac{\vec{\chi}\cdot\vec{\tau}}{2v}\right)\frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix} = U(x)\frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix}$$

such that by rotating

$$\phi \xrightarrow{U^{-1}} \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix}$$

$H \longrightarrow$ physical Higgs boson
$\vec{\chi} \longrightarrow$ reabsorbed in massive $W^{\pm}$ and Z^0

From kinetic term:

$$M_W = g\frac{v}{2} \quad \text{and} \quad M_Z = \sqrt{g^2 + g'^2}\frac{v}{2}$$

From $V(\phi)$: $M_H = -2\mu^2 = 2v^2\lambda$

Plus: WWH, ZZH, 3H, 4H interactions

SSB communicated to fermion fields

through the Yukawa Lagrangian

$$\mathcal{L}_{\text{Yukawa}} = -\lambda_d \bar{f}_L^d \phi f_R^d - \lambda_u \bar{f}_L^u \phi^c f_R^u$$

where: $\phi^c = i\tau_2 \phi$, $\lambda_{u,d} \longrightarrow$ Yukawa couplings

When

$$\phi \xrightarrow{U^{-1}} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

$$\mathcal{L}_f = -m_f \bar{f} f \left(1 + \frac{H}{v}\right)$$

fermion mass terms appear

$$m_f = \lambda_f \frac{v}{\sqrt{2}}$$

and fermion-Higgs couplings fixed to

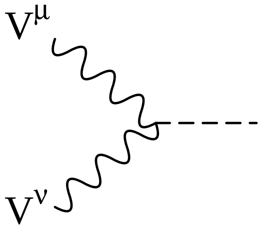
$$C_f = \frac{m_f}{v}$$

Note: v from μ-decay, $\mu^- \to e^- \bar{\nu}_e \nu_\mu$

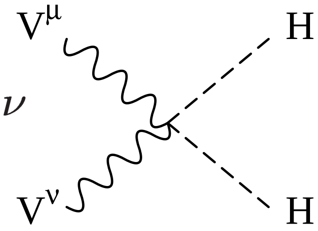
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 M_W^2} = \frac{1}{2v^2} \quad \longrightarrow \quad v \simeq 246 \text{ GeV}$$

At tree level, the SM Higgs looks like

- Couplings to EW gauge bosons ($V = W, Z$):

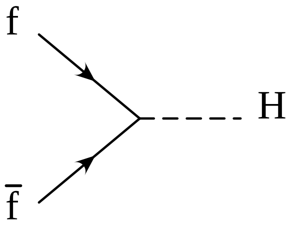


$$= 2i\frac{M_V^2}{v}g^{\mu\nu}$$



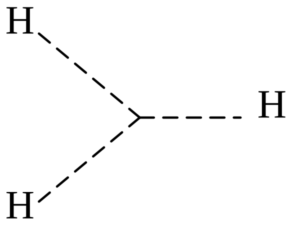
$$= 2i\frac{M_V^2}{v^2}g^{\mu\nu}$$

- Couplings to fermions ($f = l, q$):

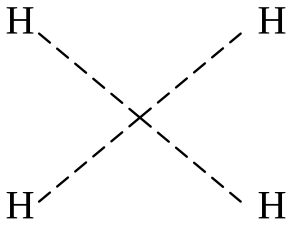


$$= -i\frac{m_f}{v}$$

- Self-couplings:



$$= -3i\frac{M_H^2}{v}$$



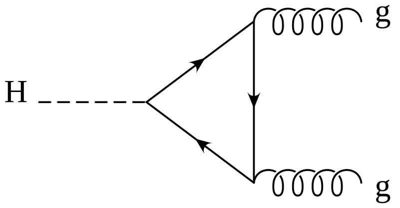
$$= -3i\frac{M_H^2}{v^2}$$

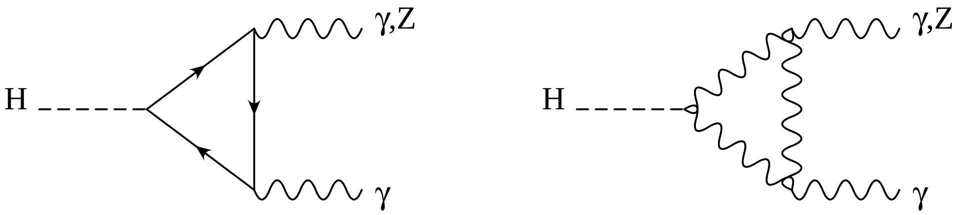
We observe that:

- ▷ Higgs boson couples mostly to heavy particles (t,b,W,Z)
- ▷ no tree level coupling to photons (γ) and gluons (g)
- ▷ $M_H^2 = 2v^2\lambda$: large $M_H \longrightarrow$ strong coupling regime

Beyond tree level

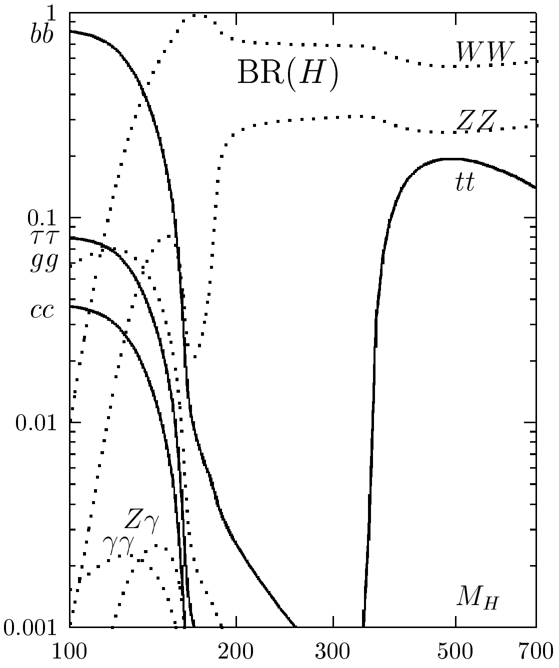
- Loop induced couplings: Hgg and $H\gamma\gamma$

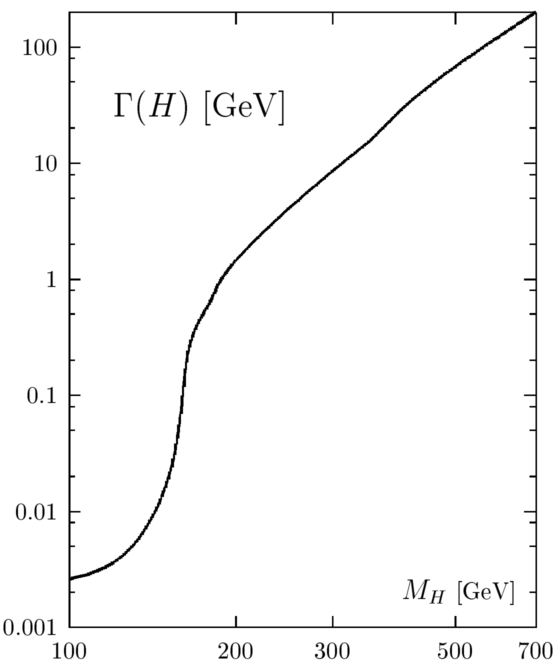




- Rates modified by radiative corrections, mainly QCD (HDECAY code: includes them)

We can now calculate





Note difference between light and heavy Higgs

SM Higgs Decay rates, Review

Tree level decays

$$\Gamma(H \to f\bar{f}) = \frac{g_{hff}^2}{4\pi} \frac{N_c M_H}{2} \beta_f^3$$

$$\Gamma(H \to VV) = \frac{g_{hVV}^2}{4\pi} \frac{3\delta_V}{8M_H} \left(1 - \frac{4}{3}\frac{1}{\tau_V} + \frac{4}{3}\frac{1}{\tau_V^2}\right) \beta_V$$

$(\tau_i = 4m_i^2/M_H^2,\ \beta_i = \sqrt{1-\tau_i},\ \delta_{W,Z} = 2, 1)$

- one-loop: complete EW and QCD corrections
- beyond one-loop: dominant corrections $(\alpha_s,\ g_{Htt},\ \lambda)$

  $\longrightarrow$ two-loop and three-loop QCD corrections

  $\longrightarrow$ $O(g_{Htt}^2)$, $O(g_{Htt}^4)$, $O(\alpha_s(m_t)g_{Htt}^2)$, $O(\alpha_s^2(m_t)g_{Htt}^2)$ corrections computed in the low-mass Higgs approximation

$$\lim_{p_H \to 0} \mathcal{A}(X \to Y + H) = \frac{1}{v} \sum_i M_i \frac{\partial}{\partial M_i} \mathcal{A}(X \to Y)$$

  $\longrightarrow$ $\mathcal{O}(\lambda^2)$ corrections for $M_H \gg 2M_Z$

Loop induced decays

$$\Gamma(H \to gg) = \frac{G_F \alpha_s^2 M_H^3}{36\sqrt{2}\pi^3} \left| \sum_Q A_Q^H(\tau_Q) \right|$$

- QCD corrections up to three loops (15-20% à la BLM)
- $\mathcal{O}(G_F M_t^2)$ EW corrections very small

$$\Gamma(H \to \gamma\gamma) = \frac{G_F \alpha^2 M_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_{cf} e_f^2 A_f^H(\tau_f) + A_W^H(\tau_W) \right|^2$$

- QCD corrections up to three loops (3% for light Higgs)
- $\mathcal{O}(G_F M_t^2)$ EW small (1%)

$\Gamma(H \to \gamma Z) \longrightarrow$ similar to $\Gamma(H \to \gamma\gamma)$

Ex. 1: $\Gamma(H \to Q\bar{Q})$, QCD corrections

Start from tree level:

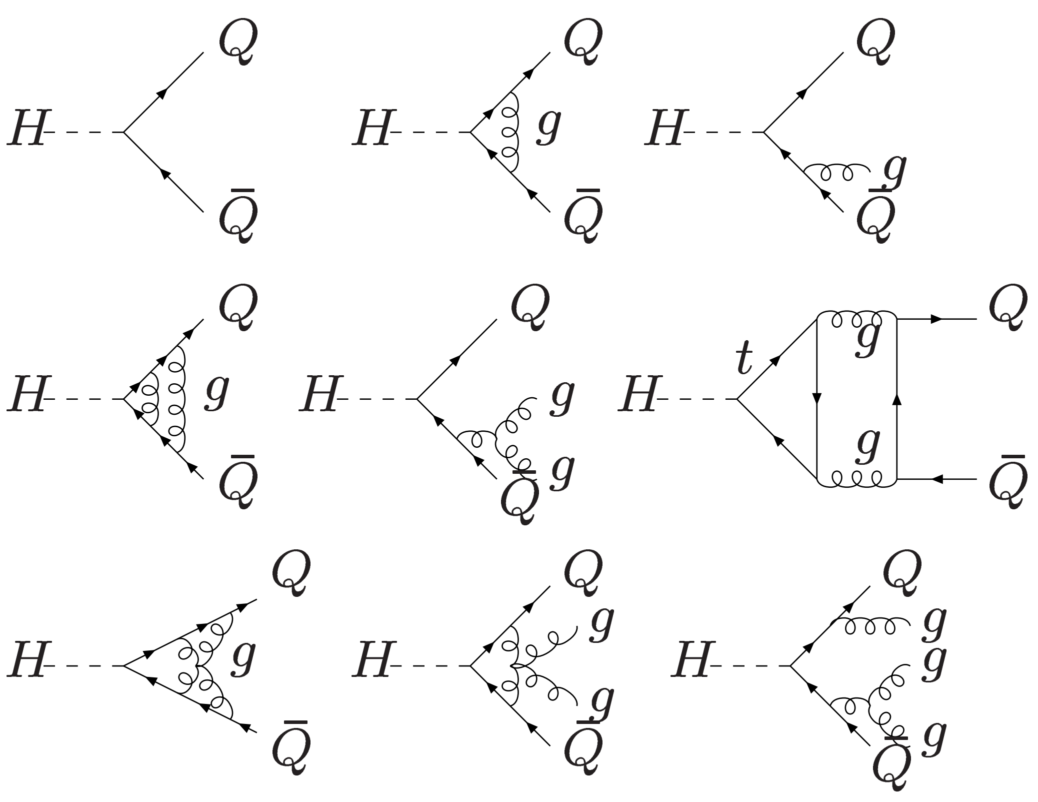
$$\Gamma(H \to Q\bar{Q})_{\text{tree}} = \frac{3G_F M_H}{4\sqrt{2}\pi} m_Q^2 \beta_Q^3$$

And add QCD corrections to a given order,

$$\Gamma(H \to Q\bar{Q})_{\text{QCD}} = \frac{3G_F M_H}{4\sqrt{2}\pi} \bar{m}_Q^2(M_H) \beta_Q^3 \left[\Delta_{QCD} + \Delta_t\right]$$

$$\begin{aligned}
\Delta_{QCD} &= 1 + 5.67\frac{\alpha_s(M_H)}{\pi} + (35.94 - 1.36N_F)\left(\frac{\alpha_s(M_H)}{\pi}\right)^2 \\
\Delta_t &= \left(\frac{\alpha_s(M_H)}{\pi}\right)^2 \left[1.57 - \frac{2}{3}\ln\frac{M_H^2}{m_t^2} + \frac{1}{9}\ln^2\frac{\bar{m}_Q^2(M_H)}{M_H^2}\right]
\end{aligned}$$

Consist of both real and virtual corrections:



- Large Logs reabsorbed into $\overline{MS}$ quark mass

$$\text{Leading Order}: \quad \bar{m}_Q(\mu) = \bar{m}_Q(m_Q)\left(\frac{\alpha_s(\mu)}{\alpha_s(m_Q)}\right)^{\frac{2b_0}{\gamma_0}}$$

$$\text{Higher order}: \quad \bar{m}_Q(\mu) = \bar{m}_Q(m_Q)\frac{f\left(\alpha_s(\mu)/\pi\right)}{f\left(\alpha_s(m_Q)/\pi\right)}$$

where (from renormalization group equation)

$$\begin{aligned}
f(x) &= \left(\frac{25}{6}x\right)^{\frac{12}{25}}[1+1.014x+\ldots] \quad \text{for} \quad m_c<\mu<m_b \\
f(x) &= \left(\frac{23}{6}x\right)^{\frac{12}{23}}[1+1.175x+\ldots] \quad \text{for} \quad m_b<\mu<m_t \\
f(x) &= \left(\frac{7}{2}x\right)^{\frac{4}{7}}[1+1.398x+\ldots] \quad \text{for} \quad \mu>m_t
\end{aligned}$$

- Large corrections, when $M_H \gg m_Q$

$m_b(m_b) \simeq 4.2$ GeV $\longrightarrow \bar{m}_b(M_H \simeq 100$ GeV$) \simeq 3$ GeV

Branching ratio smaller by almost a factor 2

- Main uncertainties:

$\longrightarrow$ $\alpha_s(M_Z)$

$\longrightarrow$ pole masses: $m_c(m_c)$, $m_b(m_b)$
(QCD sum rules,lattice)

Low-energy theorems: QCD corrections in the heavy quark limit.

- Observing that:
  - $\longrightarrow$ In the $p_H \to 0$ limit: the interactions of a Higgs boson with the SM particles arise by substituting

$$M_i \longrightarrow M_i \left(1 + \frac{H}{v}\right) \quad (i = f, W, Z)$$

  - $\longrightarrow$ a Higgs boson with zero momentum can be represented by a complex constant field (number)

- Then

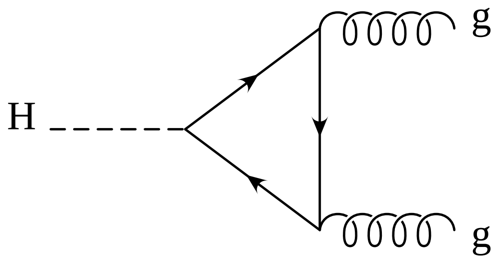
$$\lim_{p_H \to 0} \mathcal{A}(X \to Y + H) = \frac{1}{v} \sum_i M_i \frac{\partial}{\partial M_i} \mathcal{A}(X \to Y)$$

- Provided:
  - $\longrightarrow$ the differential operator does not act on M_i of the coupling
  - $\longrightarrow$ previous equation formulated in term of bare quantities

In practice: Higgs taken on shell ($p_H^2 = M_H^2$), and limit $p_H \to 0$ is limit of small Higgs masses. Very successful approximation to evaluate top quark effects for $M_H < m_t$. Compute one less order of loops.

Ex. 2: $\Gamma(H \to gg)$, QCD corrections

Start from tree level:



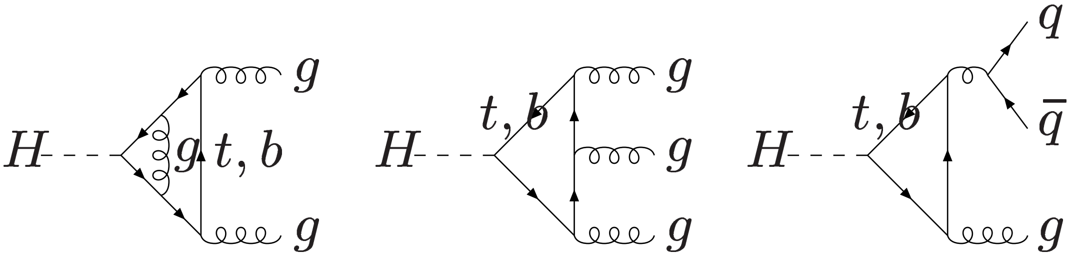
$$\Gamma(H \to gg) = \frac{G_F \alpha_s^2 M_H^3}{36\sqrt{2}\pi^3} \left| \sum_Q A_Q^H(\tau_Q) \right|$$

where

$$A_Q^H(\tau) = \frac{3}{2}\tau \left[1 + (1-\tau) f(\tau)\right]$$

$$f(\tau) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\frac{1}{4}\left[\ln \frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau < 1 \end{cases}$$

Main contribution from top quark. Then: optimal situation to use Low Energy Theorems to add QCD corrections:



- In quark gluon splitting we also have $H \to b\bar{b}g$ and $H \to c\bar{c}g$. Subtract them by using $\alpha_s(\mu)$ with $N_f = 3$

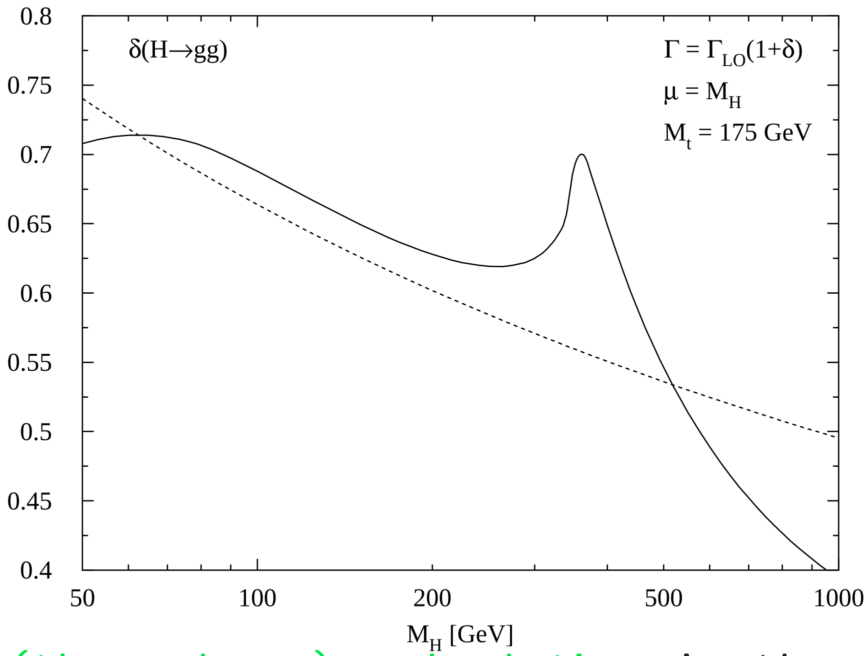
$$\alpha_s^{(5)}(\mu) = \alpha_s^{(3)}(\mu)\left[1 + \frac{\alpha_s^{(3)}}{6\pi}\left(\ln\frac{\mu^2}{m_c^2} + \ln\frac{\mu^2}{m_b^2}\right) + \ldots\right]$$

- Full massive calculation of $\Gamma(H \to gg(q), q\bar{q}g)$ agrees with $m_t \gg M_H$ result at 10%

$$\Gamma(H \to gg(q), q\bar{q}g) = \Gamma_{LO}(\alpha_s^{(N_L)}(\mu)\left[1 + E^{(N_L)}\frac{\alpha_s^{(N_L)}}{\pi}\right]$$

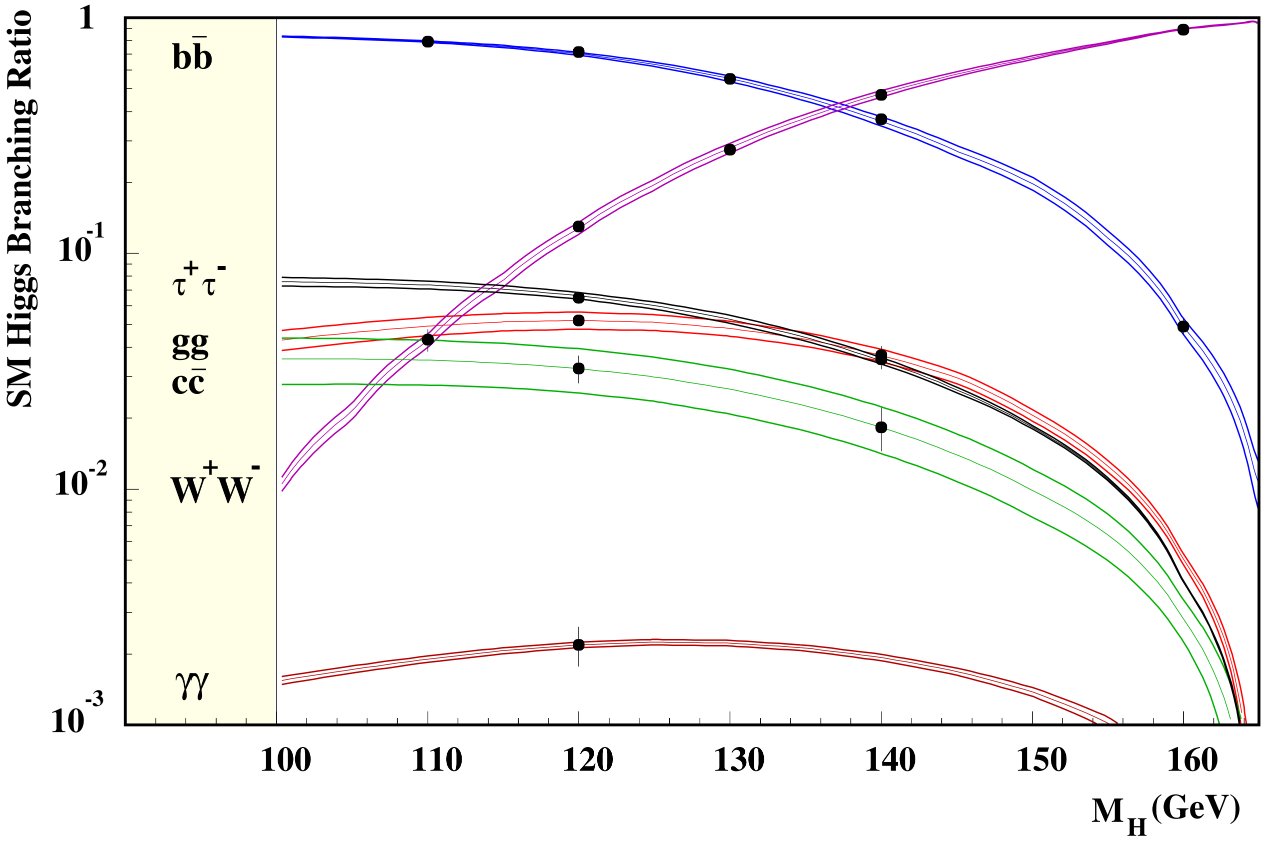
$$E^{(N_L)} = \frac{95}{4} - \frac{7}{6}N_L + \frac{33 - 2N_L}{6}\ln\frac{\mu^2}{M_H^2}$$

NLO QCD corrections almost 70% of LO result.



- NNLO (three loop) calculation in the $m_t \gg M_H$ limit add 20%: perturbative stabilization. Also: Including higher order corrections á la BLM: residual 15-20% scale dependence.

Present theoretical accuracy



Example: $M_H = 120$ GeV

Decay mode:	$b\bar{b}$	WW^*	$\tau^+\tau^-$	$c\bar{c}$	gg	$\gamma\gamma$
Theory	1.4%	2.3%	2.3%	23%	5.7%	2.3%

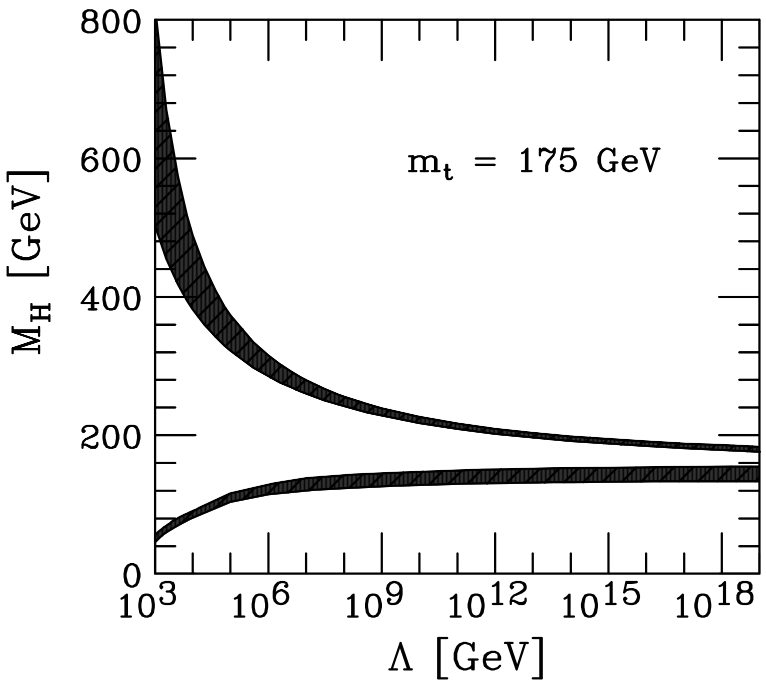
Mainly due to: pole masses m_c and m_b, and $\alpha_s(\mu)$.

From HDECAY when (Carena et al., hep-ph/0106116):

$$\alpha_s(M_Z) = 0.1185 \pm 0.0020$$
$$m_c(m_c) = 1.23 \pm 0.09 \text{ GeV}$$
$$m_b(m_b) = 4.17 \pm 0.05 \text{ GeV}$$

Consistency of the SM

$\Lambda \rightarrow$ scale of new physics



$\lambda \longleftrightarrow M_H = 2v^2\lambda$

$$\frac{d\lambda}{dt} \simeq \frac{1}{16\pi^2}\left[12\lambda^2 + \lambda\left(12g_t^2 - \frac{3}{2}(3g^2 + g'^2)\right)\right.$$
$$\left. -12g_t^4 + \frac{3}{16}\left(2g^4 + (g^2 + g'^2)^2\right)\right]$$

where $t \equiv \ln(Q^2/\Lambda^2)$ and g_t =top Yukawa coupling

- Large λ (see also lattice results):

  $$\frac{d\lambda}{dt} = 0 \quad \longrightarrow \quad \lambda_c \equiv \frac{1}{8}(3g^2 + g'2)^2 - g_t^2 \rightarrow M_{H,c}$$

  upper bound on M_H, $M_H < M_{H,c}$

- Small λ: $\lambda > 0 \longrightarrow$ vacuum stability

  lower bound on M_H, $M_H > M_{H,vs}$

The MSSM Higgs bosons

Two Higgs Doublets:

$$\phi_u = \begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix} \quad , \quad \phi_d = \begin{pmatrix} \phi_d^+ \\ \phi_d^0 \end{pmatrix}$$

Same principle, but more complex Higgs potential. Minimum occurs for

$$\langle \phi_u \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_u \end{pmatrix} \quad , \quad \langle \phi_d \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d \\ 0 \end{pmatrix}$$

Can choose v_u and v_d such that: $v^2 = v_u^2 + v_d^2$.

After field rotation, five physical Higgs bosons survive:

$$\begin{aligned} h^0 &= -(\sqrt{2}\mathrm{Re}\phi_d^0 - v_d)\sin\alpha + (\sqrt{2}\mathrm{Re}\phi_u^0 - v_u)\cos\alpha \\ H^0 &= (\sqrt{2}\mathrm{Re}\phi_d^0 - v_d)\cos\alpha + (\sqrt{2}\mathrm{Re}\phi_u^0 - v_u)\sin\alpha \end{aligned}$$

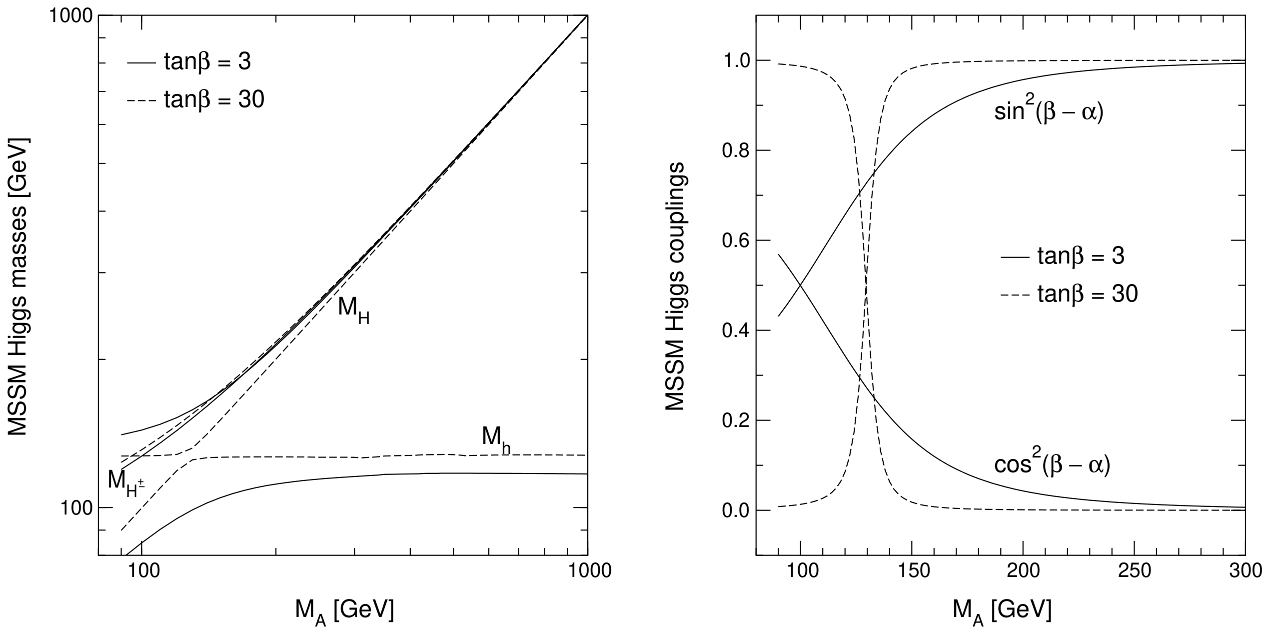
$$A^0 = \sqrt{2}\left(\mathrm{Im}\phi_d^0 \sin\beta + \mathrm{Im}\phi_u^0 \cos\beta\right)$$

$$H^\pm = \phi_d^\pm \sin\beta + \phi_u^\pm \cos\beta$$

Masses and Couplings can be worked out with the same technique seen for the SM case, only more lengthy algebra.

h^0, H^0, A^0, H^+:Masses and Couplings

Masses and couplings depend on two parameters, $(M_A, \tan\beta)$, where $\tan\beta = v_u/v_d$.



- gauge sector

$$
\begin{aligned}
g_{h^0VV} &= g_{HVV}\sin(\beta-\alpha) \;, \\
g_{H^0VV} &= g_{HVV}\cos(\beta-\alpha) \;, \quad g_{A^0VV} = 0
\end{aligned}
$$

- fermion sector

$$
\begin{aligned}
g_{h^0uu} &= g_{Huu}\frac{\cos\alpha}{\sin\beta} \;, \quad g_{h^0dd} = g_{Hdd}\frac{-\sin\alpha}{\cos\beta} \;, \\
g_{H^0uu} &= g_{Huu}\frac{\sin\alpha}{\sin\beta} \;, \quad g_{H^0dd} = g_{Hdd}\frac{\cos\alpha}{\cos\beta} \;, \\
g_{A^0uu} &= g_{Huu}\frac{1}{\tan\beta} \;, \quad g_{A^0dd} = g_{Hdd}\tan\beta \;,
\end{aligned}
$$

plus loop effects

MSSM Higgs Decay rates, beyond tree level

Besides obvious rescaling of the couplings...

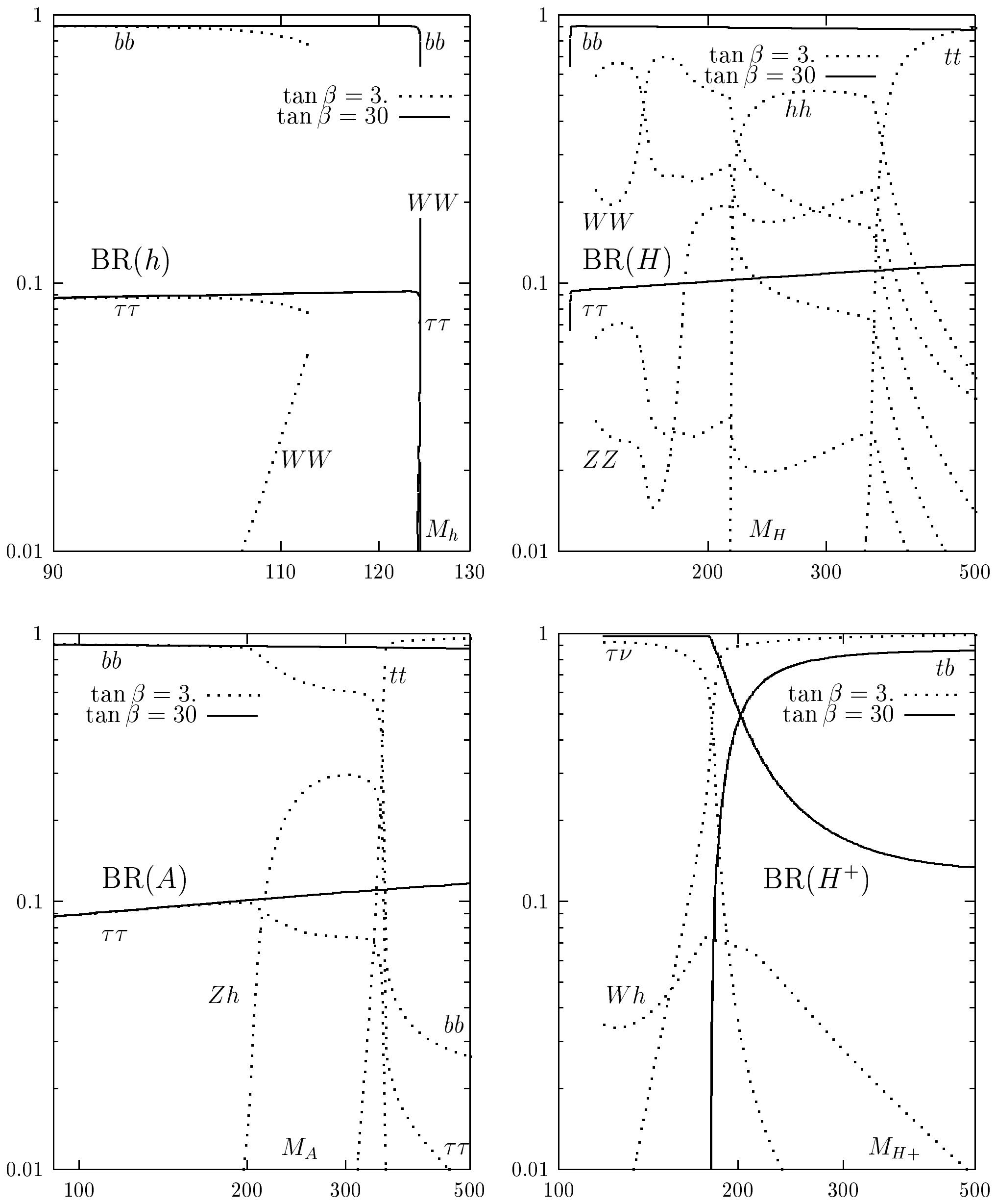
- $\Gamma(\Phi^0 \to f\bar{f})$ and $\Gamma(H^\pm \to f'\bar{f})$
  $\longrightarrow$ QCD corrections as SM
  $\longrightarrow$ full MSSM EW and QCD corrections: usually $< 10\%$, except large gluino contributions for large $\tan\beta$ and $M_{\tilde{q}} < 300$ GeV.

- $\Gamma(\Phi^0 \to gg)$: b-quark loop and squark loop can be important
  $\longrightarrow$ QCD corrections as SM

- $\Gamma(\Phi^0 \to \gamma\gamma)$: additional sfermion, chargino, and charged Higgs loops
  $\longrightarrow$ QCD corrections normally small
  $\longrightarrow$ no complete MSSM corrections

- Decays to MSSM particles

Much more complicated scenario



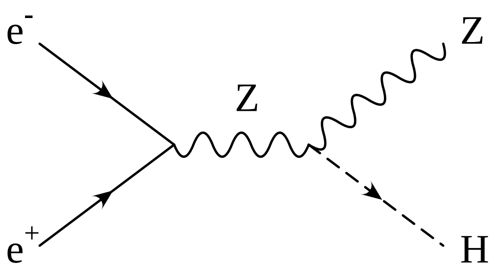
but theoretical upper bound on M_{h^0}

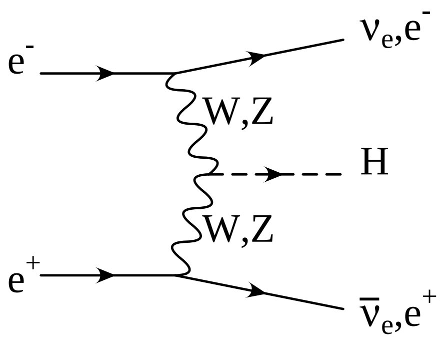
$$M_{h^0} < 135\,\text{GeV}$$

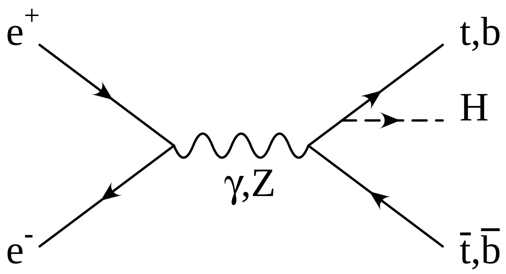
i.e., need evidence for one light scalar Higgs boson.

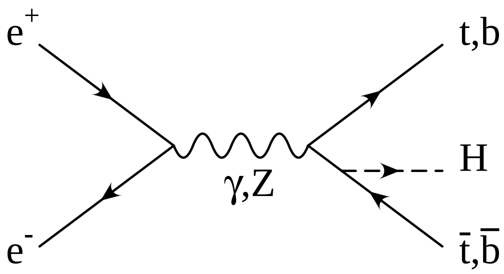
Higgs boson production:
past, present, and future colliders

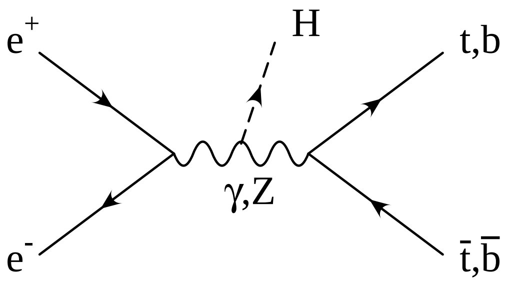
e^+e^- colliders: production modes



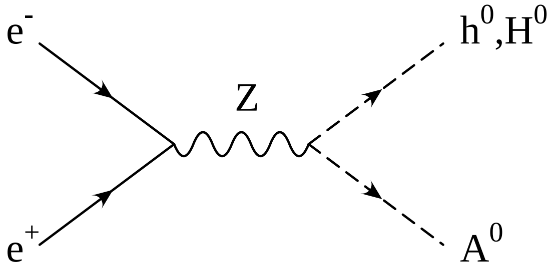


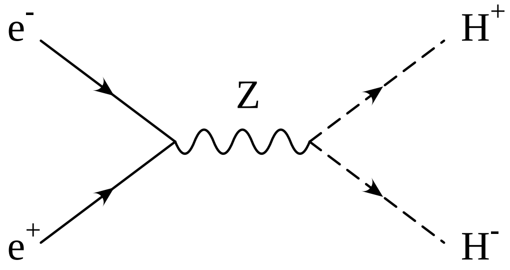






and additional MSSM modes

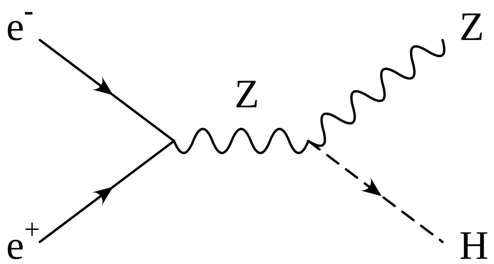


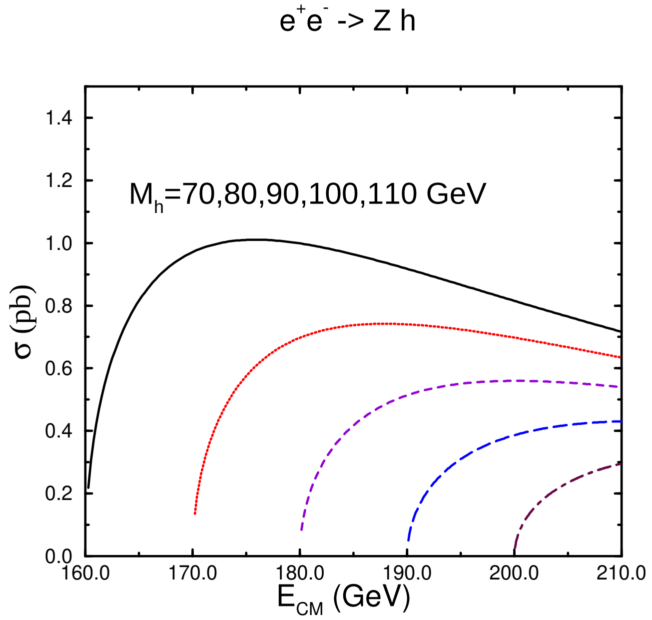


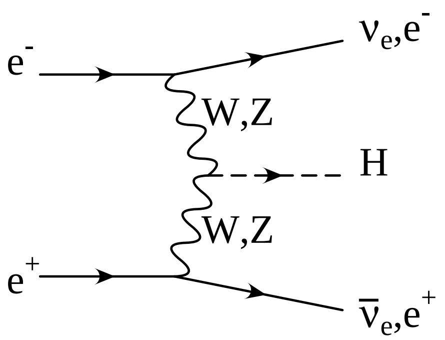
LEP: Direct Search

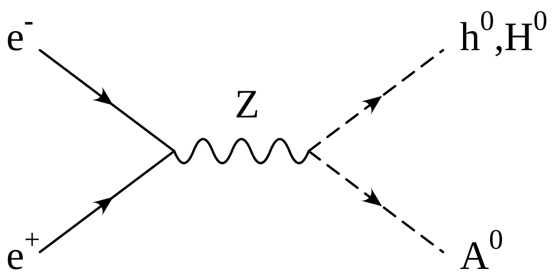
Main search modes ($H \to$all and $H \to b\bar{b}$):

- $e^+e^- \to ZH \quad (H \leftrightarrow h^0, H^0)$
- $e^+e^- \to H\nu_e\bar{\nu}_e, He^+e^- \quad (H \leftrightarrow h^0, H^0)$
- $e^+e^- \to h^0A^0, H^0A^0$ (MSSM only)









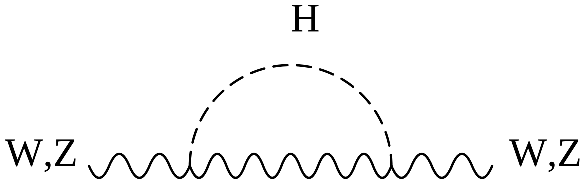
$$\sqrt{s_{\max}} = 206 \text{ GeV} \left\{ \begin{array}{l} M_H > 114.1 \text{ Gev} \quad (95\% \text{ c.l.}) \\ M_{h^0/H^0} > 91.0 \text{ GeV}, M_{A^0} > 91.9 \text{ GeV} \end{array} \right.$$

LEP: Precision EW Measurements

M_H dependence in EW radiative corrections

- SM needs Higgs boson to cancel infinities,

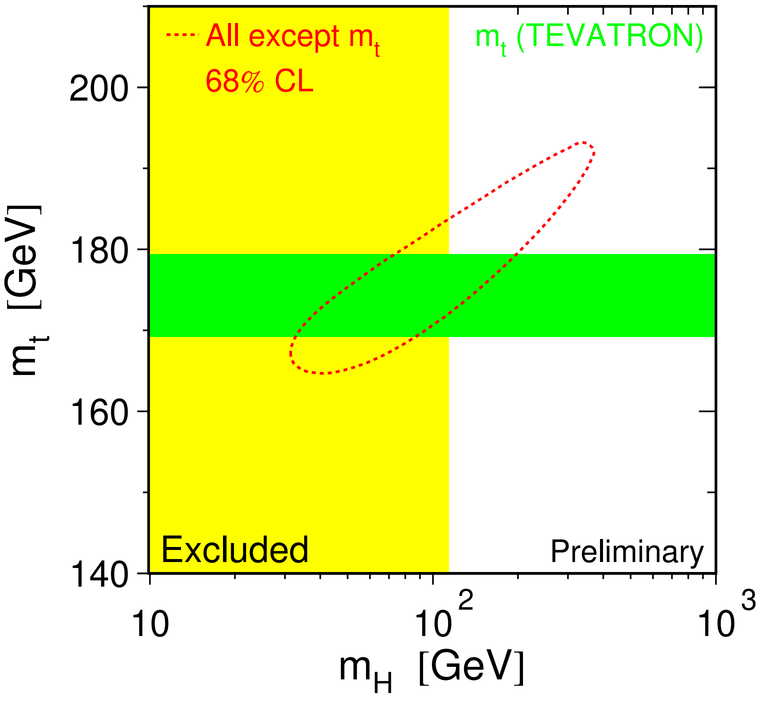
  e.g. $M_W, M_Z \longrightarrow$

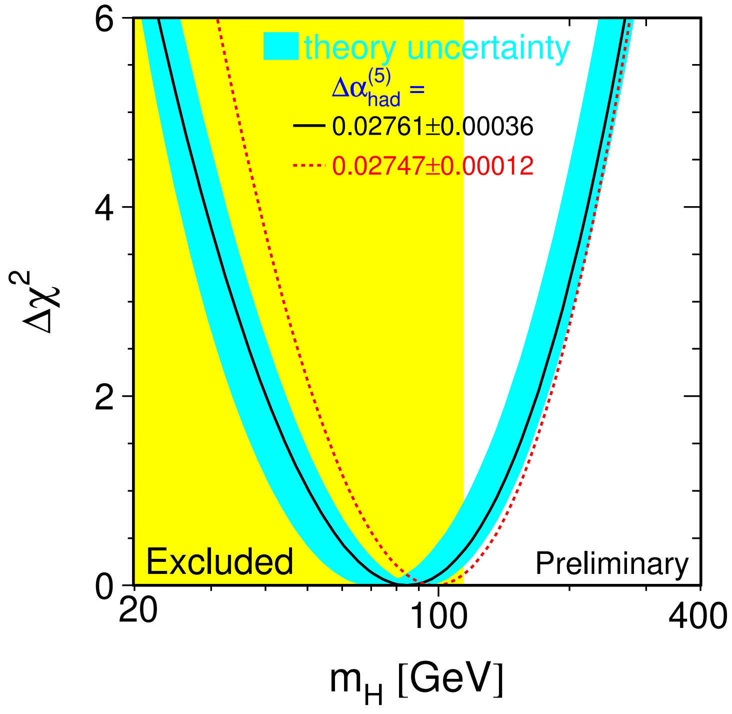


- Finite logarithmic contributions survives, e.g. radiative corrections to M_W^2/M_Z^2:

$$\delta\rho = 1 - \frac{11g^2}{96\pi^2}\tan^2\theta_W \ln\left(\frac{M_H}{M_W}\right)$$

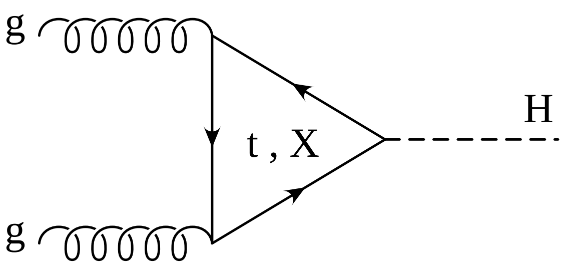
- combined fits of all EW observables constrain M_H (SM): $M_H < 196$ GeV



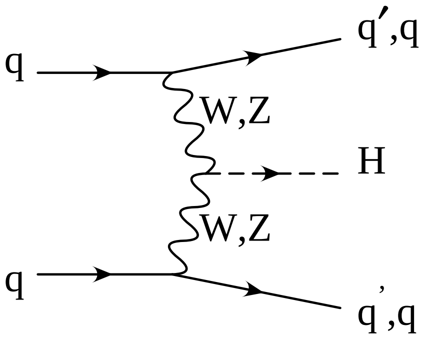


$p\bar{p}, pp$ colliders: production modes

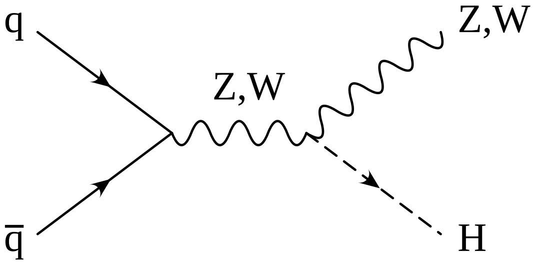
$gg \rightarrow H$



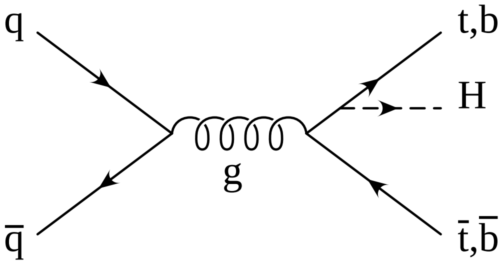
$qq \rightarrow qqH$

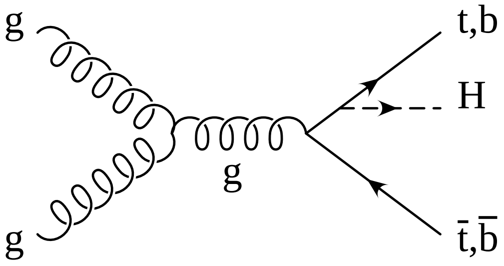


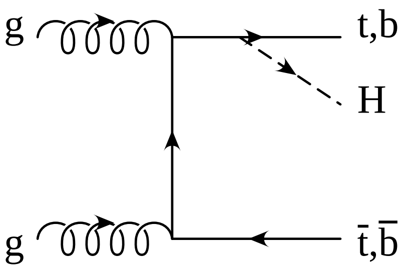
$qq \rightarrow WH, ZH$

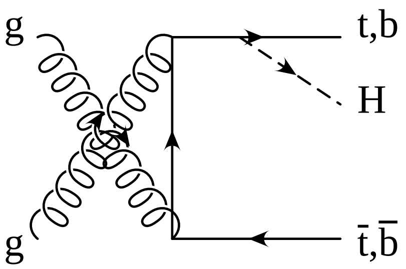


$q\bar{q}, gg \rightarrow t\bar{t}H, b\bar{b}H$



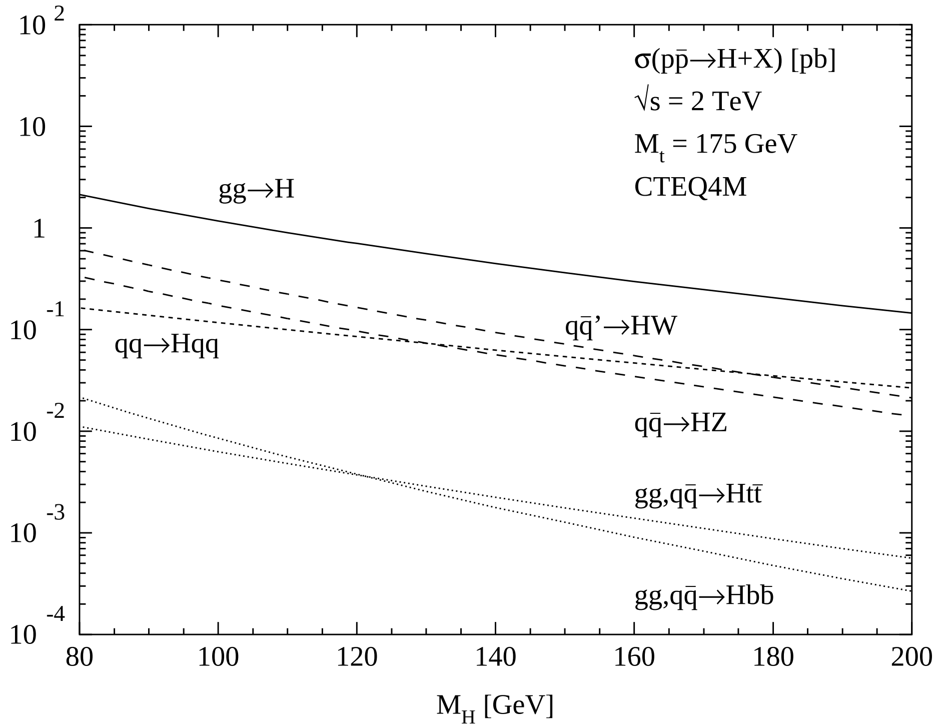


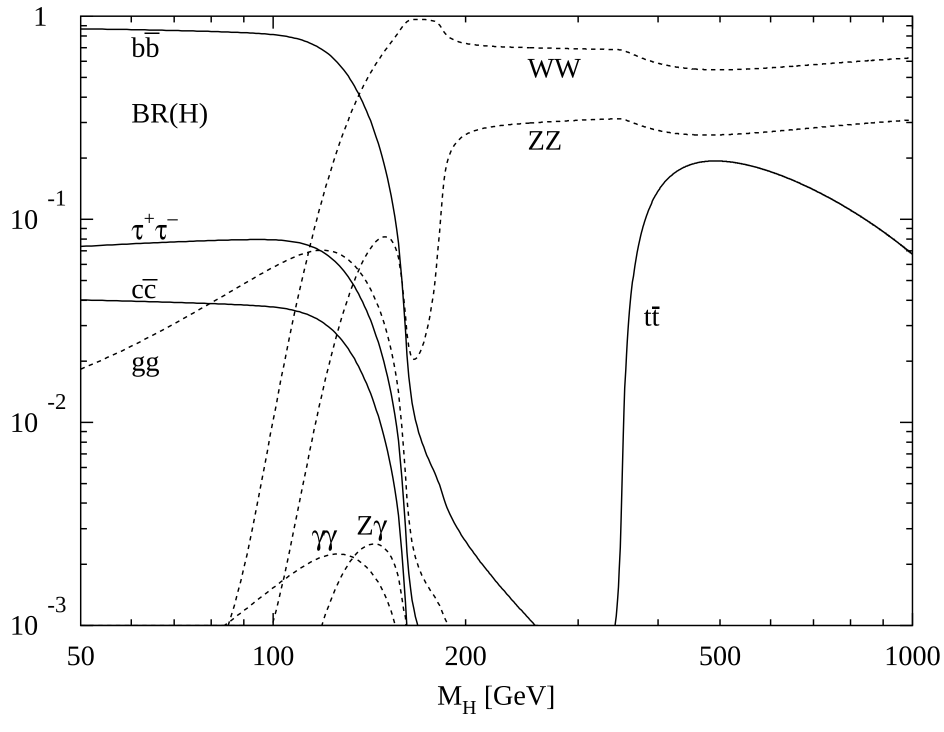




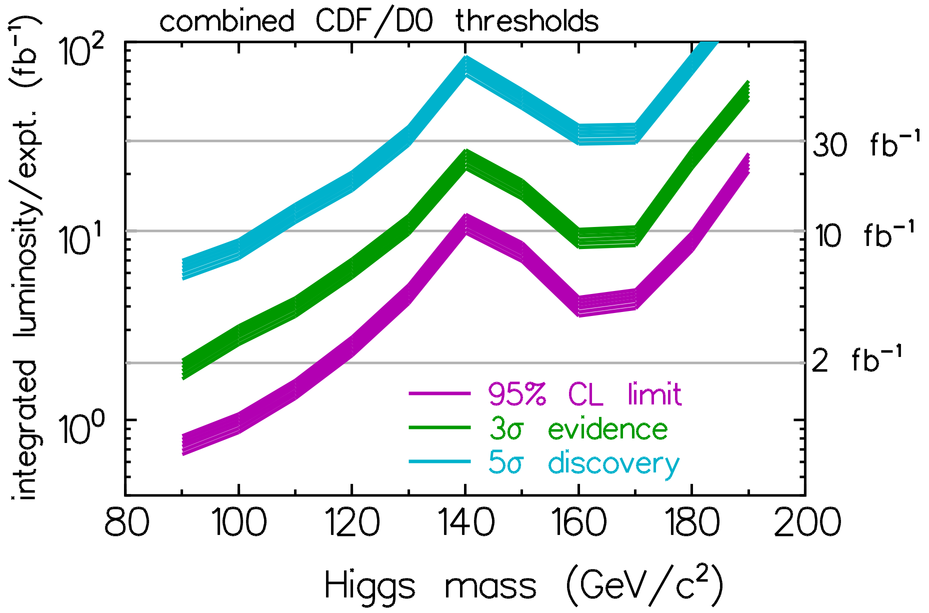
Present and close Future: Tevatron Run II ($\sqrt{s}$=2 TeV)

Production of a SM-like Higgs boson





Reach of the Tevatron, Run II



Mainly in:

- Below 130-140 GeV
  $q\bar{q} \to VH.\, H \to b\bar{b}$ with $V = Z, W$
- Above 130-140 GeV
  $q\bar{q} \to VH,\ H \to WW$ with $V = Z, W$

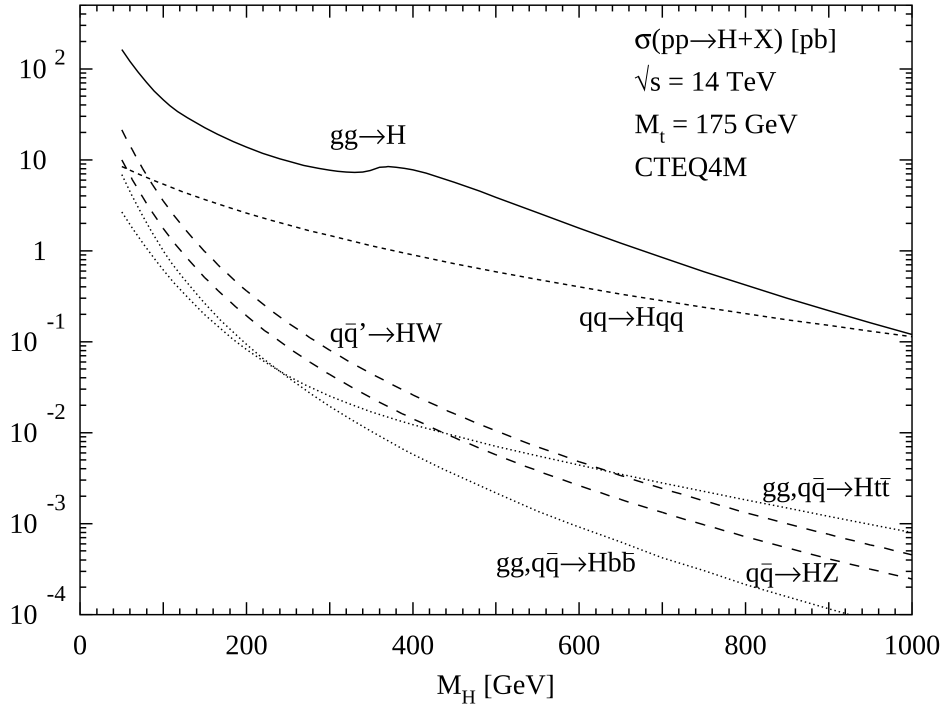
But also:

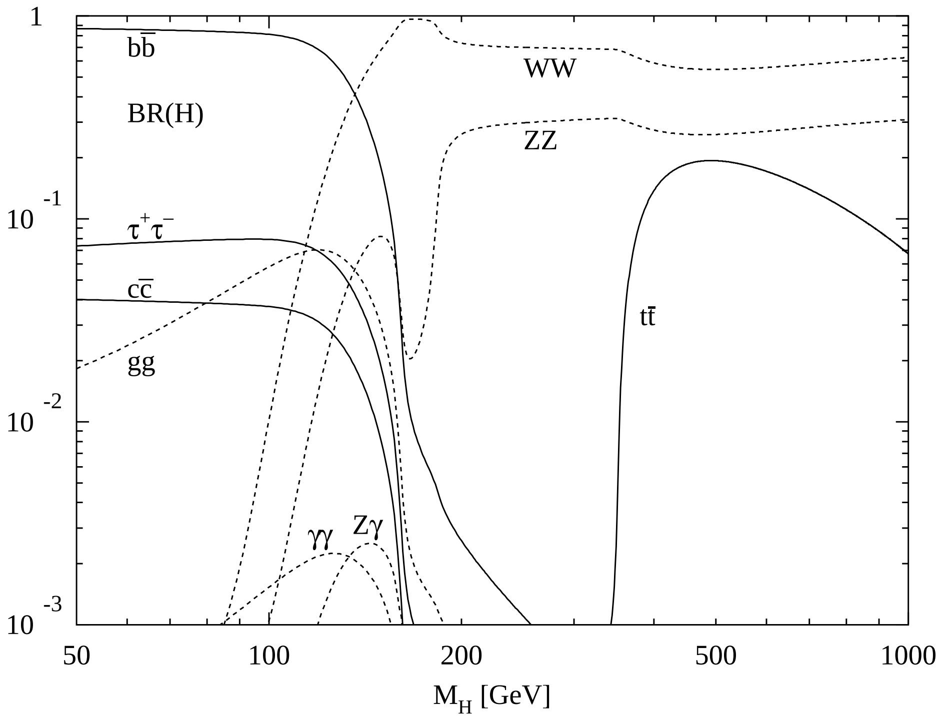
- $gg \to H$ (above 130 GeV)
- $q\bar{q} \to t\bar{t}H$ (both $H \to b\bar{b}$ and $H \to WW$)

Too low statistics to measure Higgs couplings.

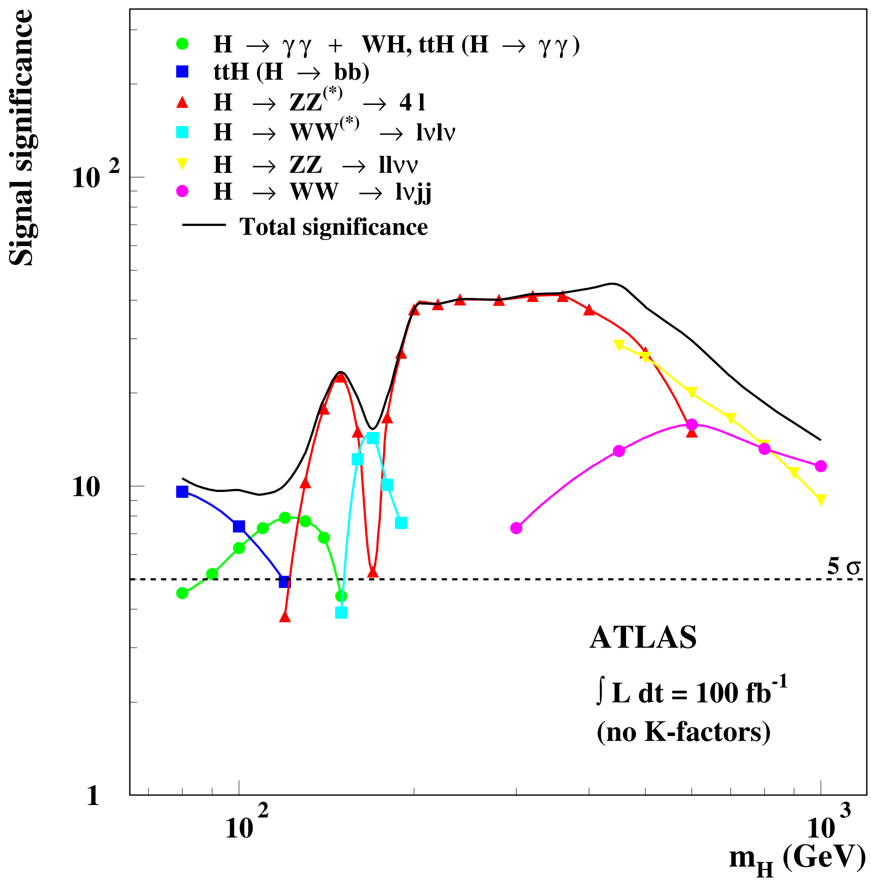
Future: the LHC ($\sqrt{s}=14$ TeV)

Production of a SM-like Higgs boson





Reach for discovery at the LHC



Measure couplings at the 10-20% level.

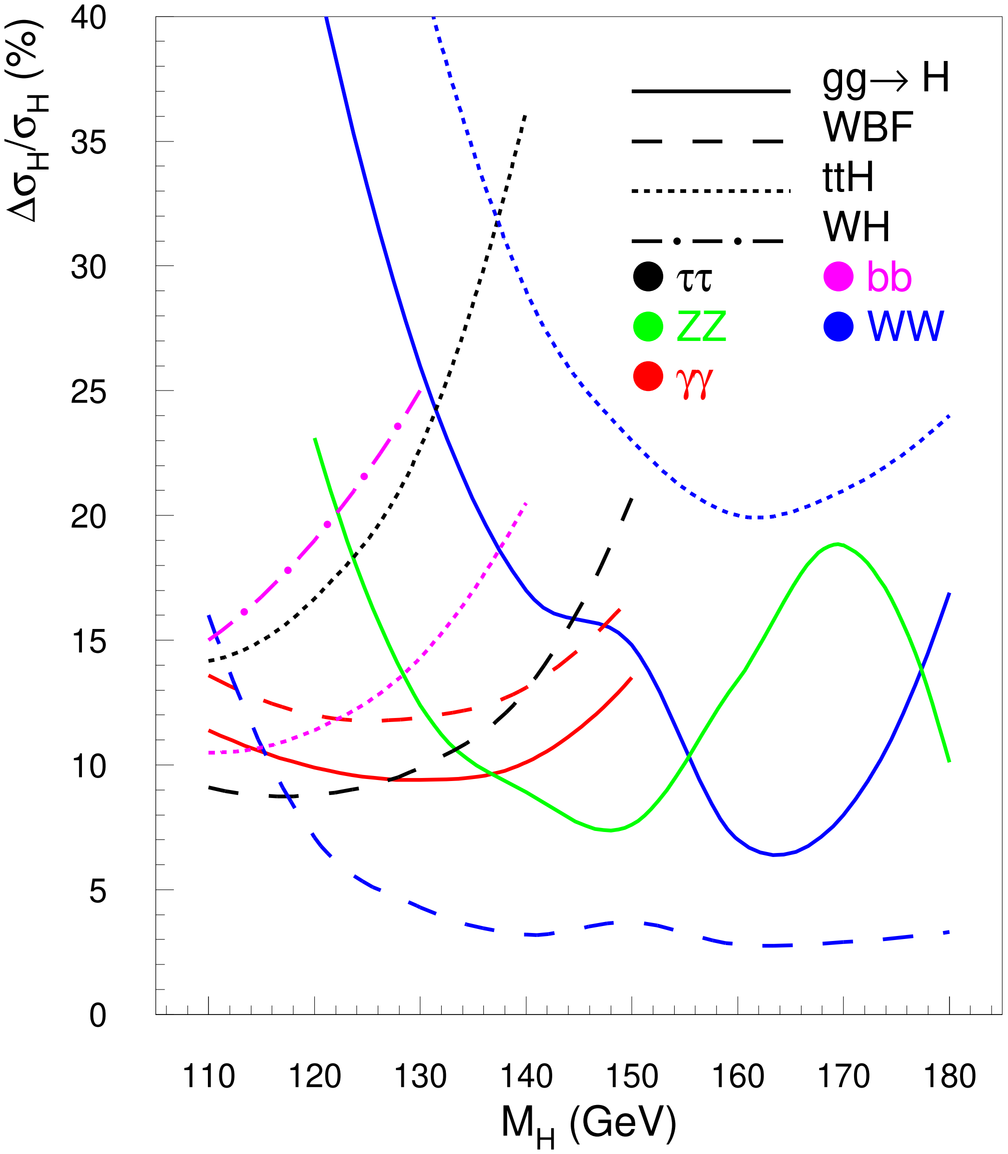
- Below 130-140 GeV

$$
\begin{aligned}
gg &\rightarrow H\,,\ H \rightarrow \gamma\gamma, W^+W^-, ZZ \\
qq &\rightarrow qqH\,,\ H \rightarrow \gamma\gamma, W^+W^-, ZZ, \tau^+\tau^- \\
q\bar{q}, gg &\rightarrow t\bar{t}H\,,\ H \rightarrow b\bar{b}, \tau^+\tau^-
\end{aligned}
$$

- Above 130-140 GeV

$$
\begin{aligned}
gg &\rightarrow H\,,\ H \rightarrow W^+W^-, ZZ \\
qq &\rightarrow qqH\,,\ H \rightarrow \gamma\gamma, W^+W^-, ZZ \\
q\bar{q}, gg &\rightarrow t\bar{t}H\,,\ H \rightarrow W^+W^-
\end{aligned}
$$

Given existing simulated accuracies

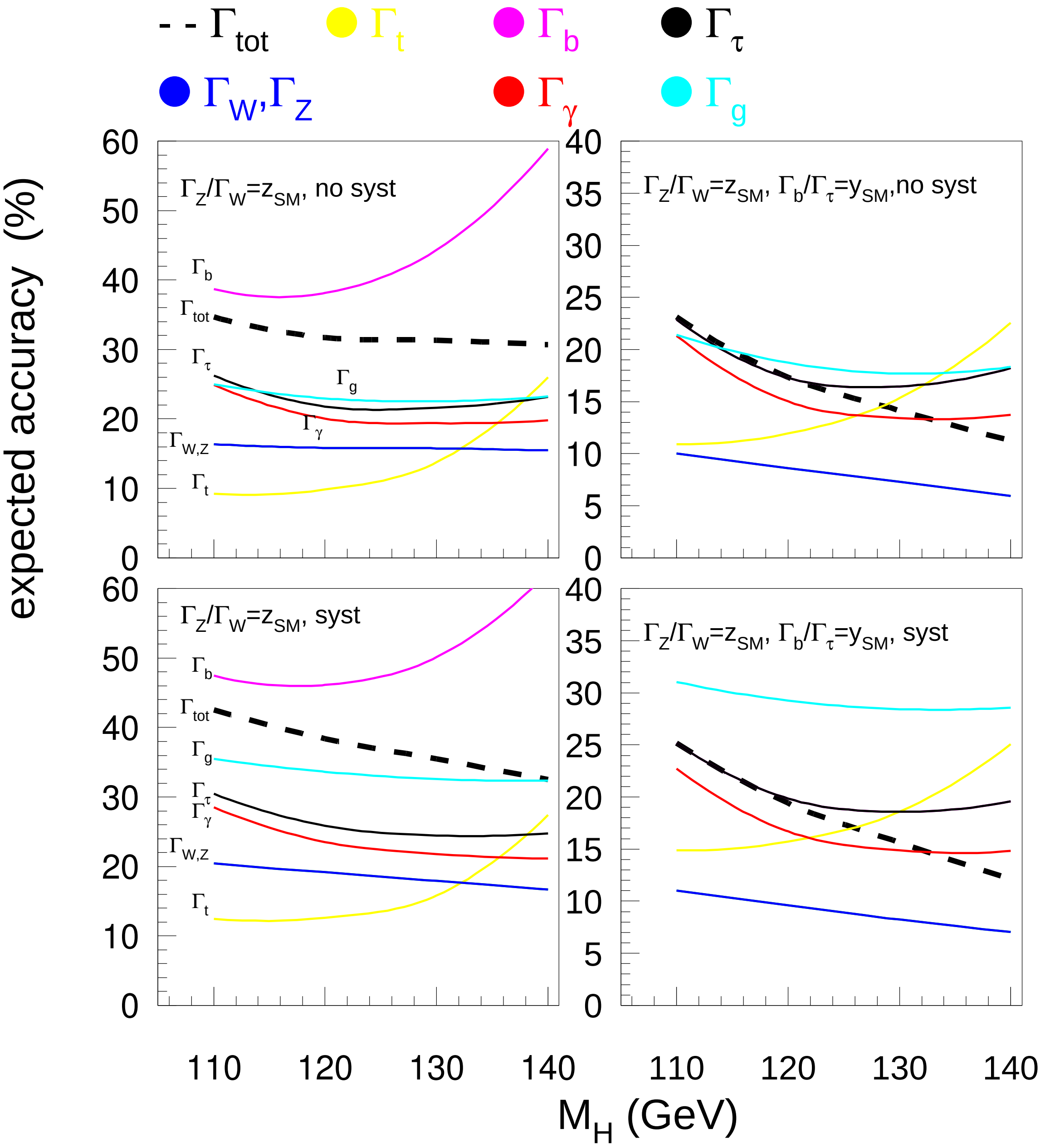


associate to each channel

$$Z_j^{(i)} = \frac{\Gamma_i \Gamma_j}{\Gamma} \qquad \begin{cases} \Gamma_i \simeq g^2_{Hii} \rightarrow \text{production} \\ \Gamma_j \simeq g^2_{Hjj} \rightarrow \text{decay} \end{cases}$$

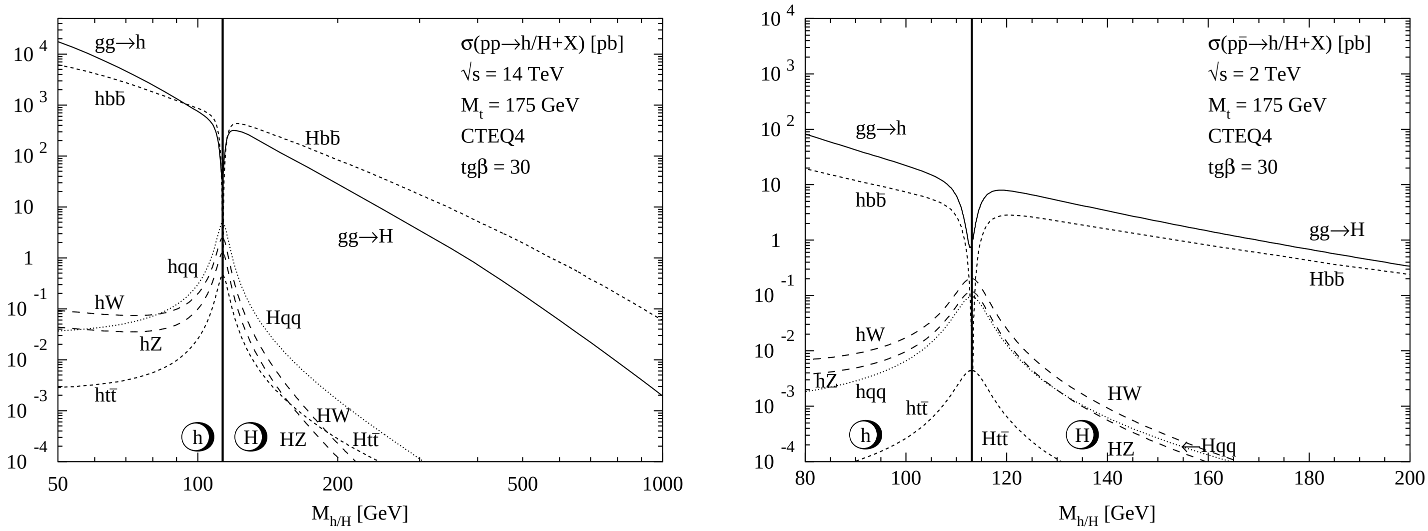
and determine $\Gamma_t, \Gamma_b, \Gamma_\tau, \Gamma_w, \Gamma_g, \Gamma_\gamma$ and Γ

One obtains the following accuracies on Couplings and Width of a Higgs boson with $M_H < 140$ GeV



$$\text{systematics} \begin{cases} gg \to H \longrightarrow 20\% \\ qq \to qqH \longrightarrow 5\% \\ pp \to t\bar{t}H \longrightarrow 10\% \end{cases}$$

Brief look at the MSSM case



- Large contributions from $q\bar{q}, gg \to b\bar{b}h^0, H^0, A^0$ for large $\tan\beta$

- Reduced couplings to the EW gauge bosons: problem at the Tevatron

- Light scalar Higgs: similar to SM in the decoupling limit

This incredible Physics Program can be impaired by not knowing the effect of QCD corrections

Some Important Facts

- In hadronic production modes QCD effects can be very large.

- Tree level or Leading Order (LO) cross sections normally have very large uncertainties due to:
  - renormalization/factorization scale dependence
  - uncertainties from PDF's

- Differential cross sections very sensitive to higher order QCD corrections.

- Main modes have very large QCD background. Realistic studies, including higher order QCD corrections, are vital to a correct estimate of the background.

- For sake of clarity, focus on SM-like Higgs, and add remarks on MSSM Higgs(es) when interesting.

- Understand the structure of higher order QCD calculations to improve on existing analyses. Review some of the most important features of the leading production modes

Calculating a hadronic cross section at NLO in QCD

NLO total cross section:

$$\sigma^{NLO}_{p\bar{p},pp} = \sum_{i,j} \int dx_1 dx_2 \mathcal{F}^p_i(x_1) \mathcal{F}^{\bar{p},p}_j(x_2) \hat{\sigma}^{NLO}_{ij}(x_1, x_2)$$

where

$$\hat{\sigma}^{NLO}_{ij} = \hat{\sigma}^{LO}_{ij} + \frac{\alpha_s}{4\pi} \delta\hat{\sigma}^{NLO}_{ij}$$

is NLO partonic cross section $\hat{\sigma}(ij \to \ldots)$, and $\mathcal{F}^{\bar{p},p}_j(x)$ are NLO Parton Distribution Functions.

- NLO corrections made of:

  $$\delta\hat{\sigma}^{NLO}_{ij} = \hat{\sigma}^{ij}_{virt} + \hat{\sigma}^{ij}_{real}$$

  and NLO PDF's.

- In particular, one needs to:
  - ▷ renormalize UV divergences in $\hat{\sigma}_{virt}$
  - ▷ cancel IR divergences in $\hat{\sigma}_{virt} + \hat{\sigma}_{real}$
  - ▷ check μ-dependence of σ^{NLO}

- Improve calculation by resumming large logarithms from phase space integration, if necessary.

Usual to parameterize the impact of QCD corrections introducing a K-factor

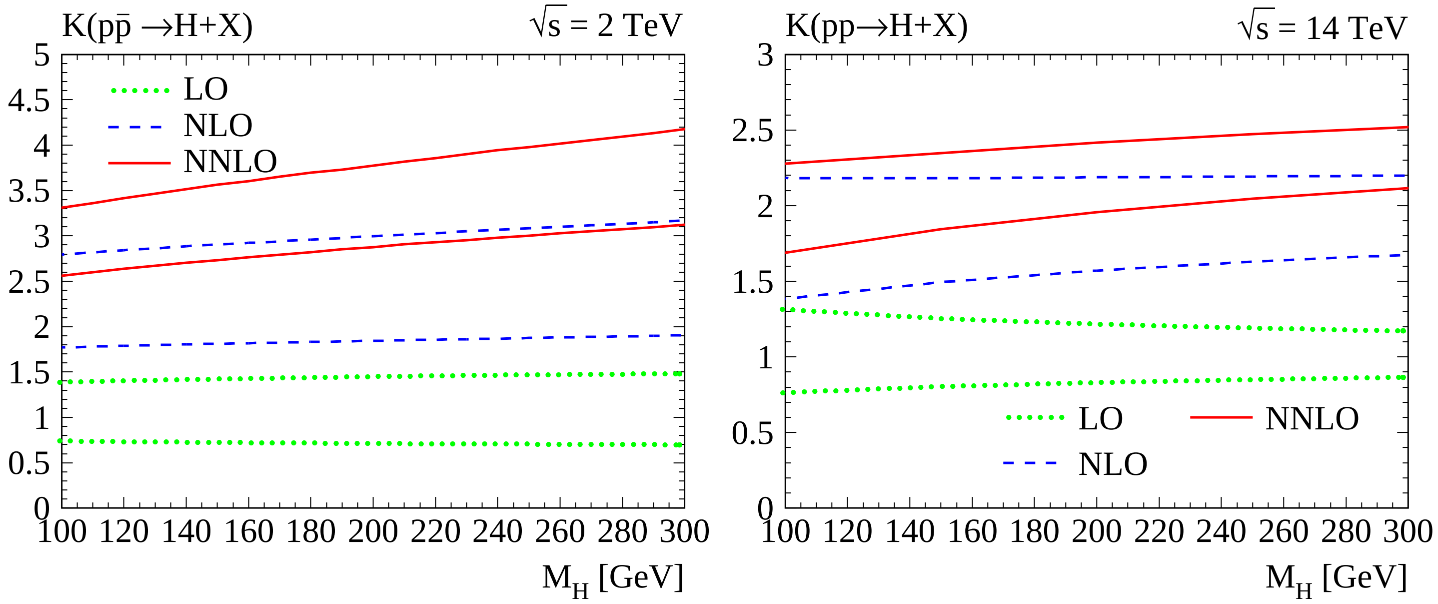
$$K = \frac{\sigma_{NLO}}{\sigma_{LO}}$$

Be aware that:

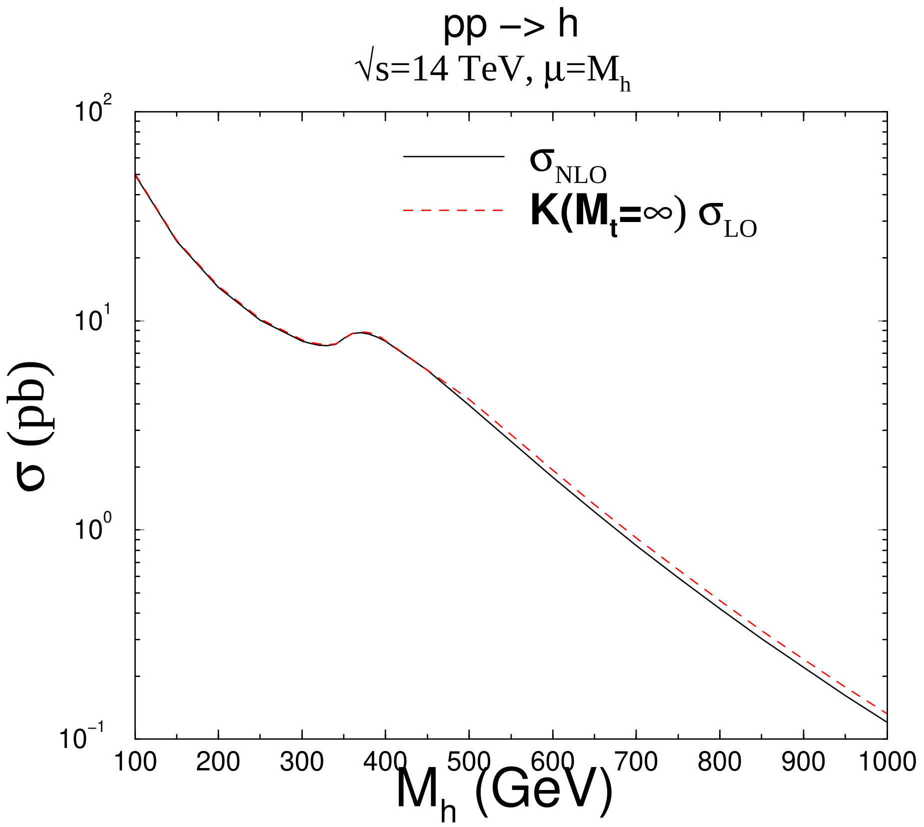
- K-factors are scale dependent objects. In fact, they have a pretty strong scale dependence: you need to be consistent.
- In general you cannot use K-factors to rescale LO phase space distributions (unless you have good reasons to do that)
- Low Energy Theorems and Effective Higgs Approximations tipically very good at predicting K-factors (i.e. total cross sections, and cross sections ratios), not distributions.

$gg \to H$: the leading production mode

- ggH effective coupling can probe new physics (MSSM: squark loops, extra-dimensions)
- NLO QCD corrections almost double the LO cross section
- NNLO QCD corrections computed using soft limit and Low Energy Theorem (i.e. large m_t limit, remember $H \to gg$): uncertainty within 15-20% at least.



The $m_t \to \infty$ approximation works to better than 10% at NLO, and expected to do so also at NNLO. This approximation works because QCD corrections to $gg \to H$ are dominated by soft and collinear gluon effects (they do not resolve the Hgg coupling).



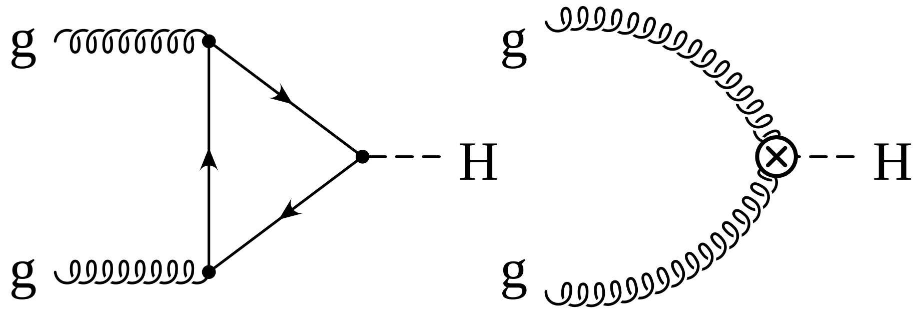
In the soft limit, for $x \equiv M_H^2/\hat{s} \to 1$

$$\hat{\sigma}_{ij} = \sum_{n \geq 0} \left(\frac{\alpha_s}{\pi}\right)^n \hat{\sigma}_{ij}^{(n)}$$

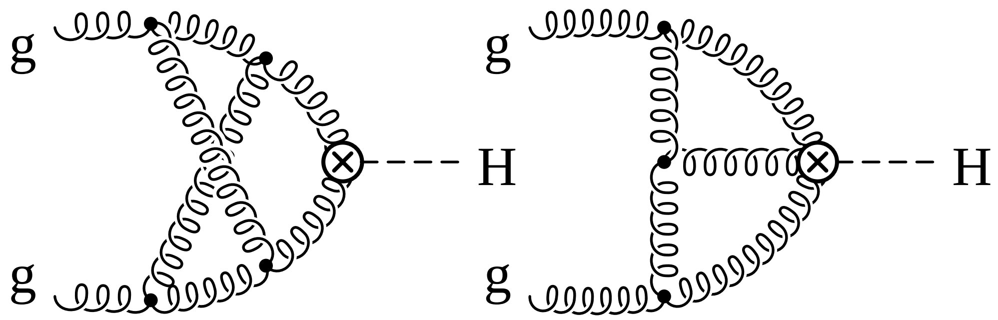
$$\begin{aligned} \hat{\sigma}_{ij}^{(n)} &= a^{(n)}\delta(1-x) + \sum_{k=0}^{2n-1} b_k^{(n)} \left[\frac{\ln^k(1-x)}{1-x}\right]_+ \\ &+ \sum_{l=0}^{\infty} \sum_{k=0}^{2n-1} c_{lk}^{(n)} (1-x)^l \ln^k(1-x) \end{aligned}$$

the first two series of terms provide the bulk of the leading corrections, while the last series represents sub-leading collinear contributions.

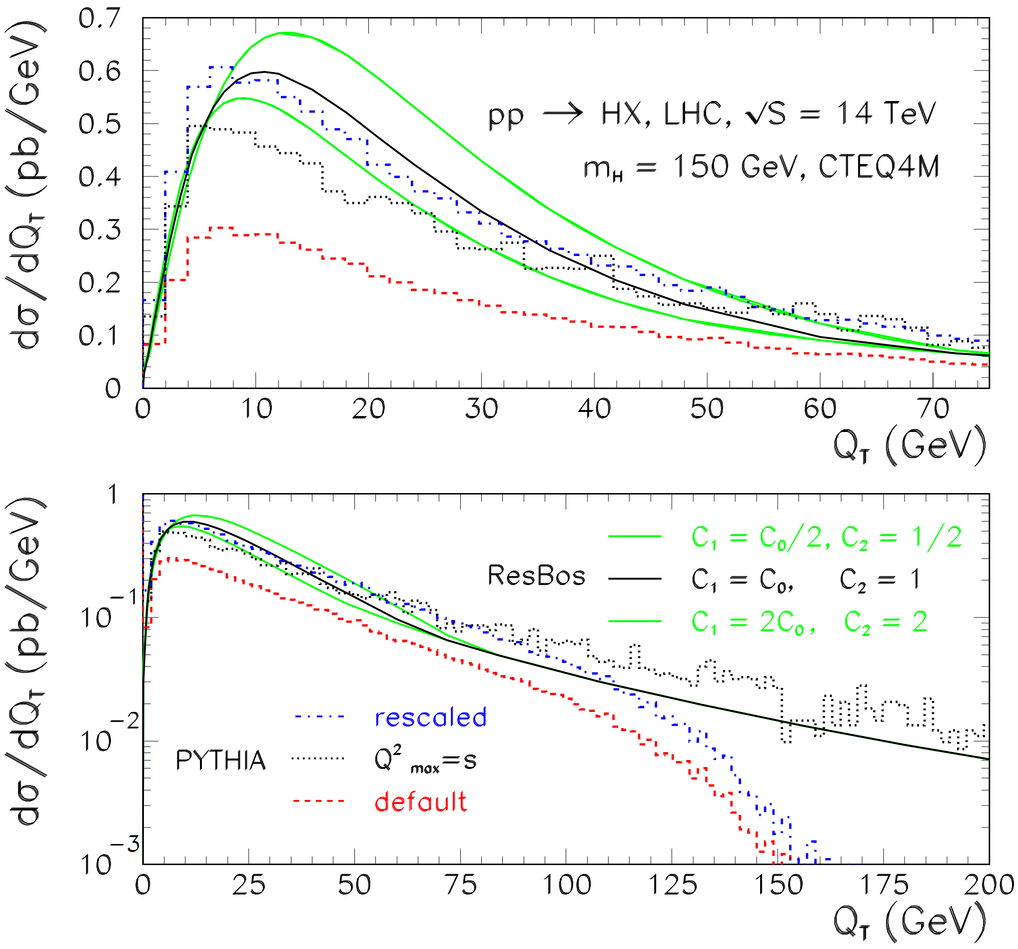
$m_t \to \infty$ approximation at tree level



$m_t \to \infty$ approximation at loop level



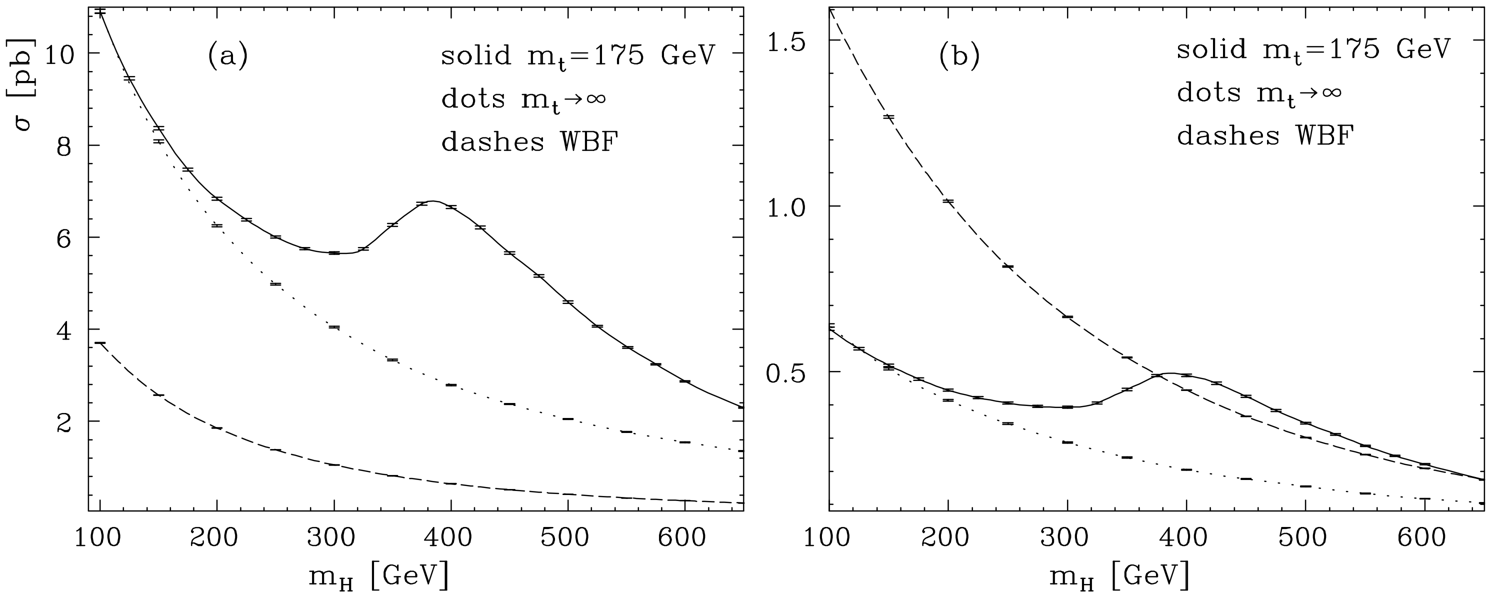
- Very large QCD background, need to use:
  - $H \to \gamma\gamma$ for $M_H \leq 130$ GeV
    Very narrow signal pick. Easy to interpolate main $gg \to \gamma\gamma$ background from sidebands (also know at NLO of QCD)
  - $H \to WW \to l^+ l^- \not{p}_T$ for $M_H > 130$ GeV
    Very broad distribution, because of $\not{p}_T$:
    Cuts spoil the consistency of the NLO or NNLO cross sections, introducing very large scale dependence: problem of getting NLO and NNLO differential cross sections.
  - $H \to ZZ \to 4l^\pm$ for $M_H > 130$ GeV
    very narrow signal pick, background from the sidebands



- QCD changes Higgs p_T spectrum
  - ▷ Higgs has no p_T at lowest order
  - ▷ At higher order, effects of soft and collinear gluons are significant: need to resum them at low p_T, and match with the exact matrix element calculation at larger p_T
  - ▷ crucial to understand how these effects are included in experimental Monte Carlo programs.

$qq \to qqH$: great potential

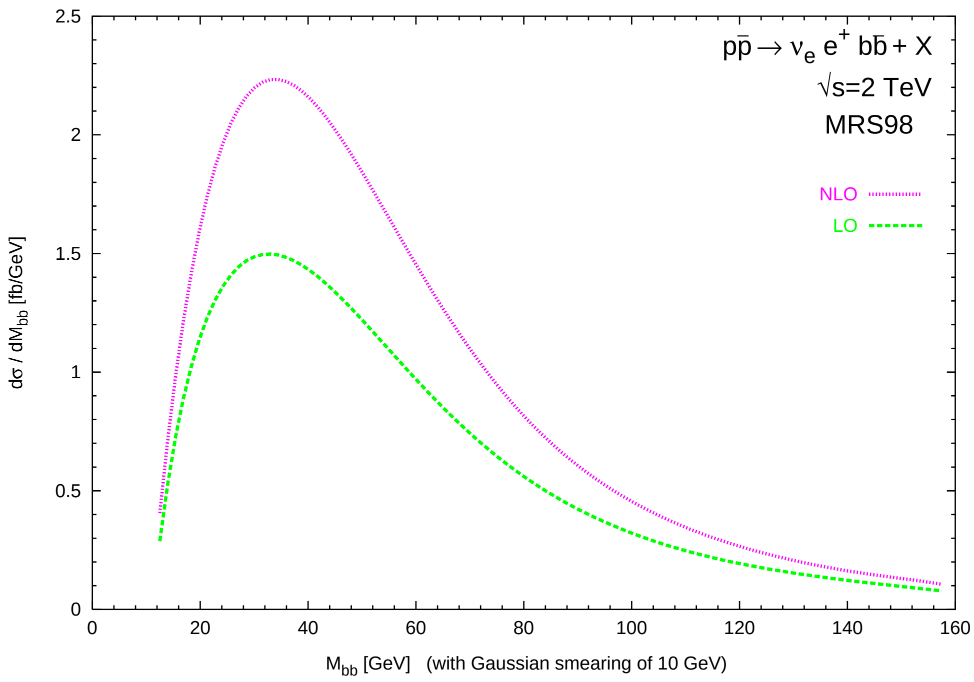
- NLO corrections: corrections to DIS structure functions, small (10%) and under control
- signal selection uses forward jet tagging and central jet veto
- Large $H + 2J$ background, in particular $gg \to ggH$ (mainly top quark loop). Now fully calculated.



Allows clear estimate of the impact of cuts devised to enhanced the jet anisotropy of $qq \to qqH$ signal.

$q\bar{q}, qq \to HW, HZ$

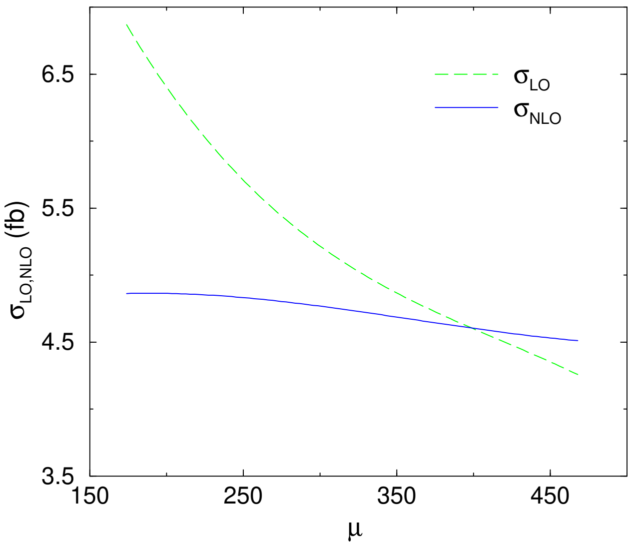
- Crucial production mode for Higgs search at the Tevatron (with $H \to b\bar{b}$)
- NLO QCD corrections are like Drell-Yan, amount to 30% of LO, with a residual 12% uncertainty.
- Important background: $p\bar{p} \to Wb\bar{b}, Zb\bar{b}$. Now calculated at NLO and included into MCFM Monte Carlo. Important NLO effects in $b\bar{b}$ mass distribution.

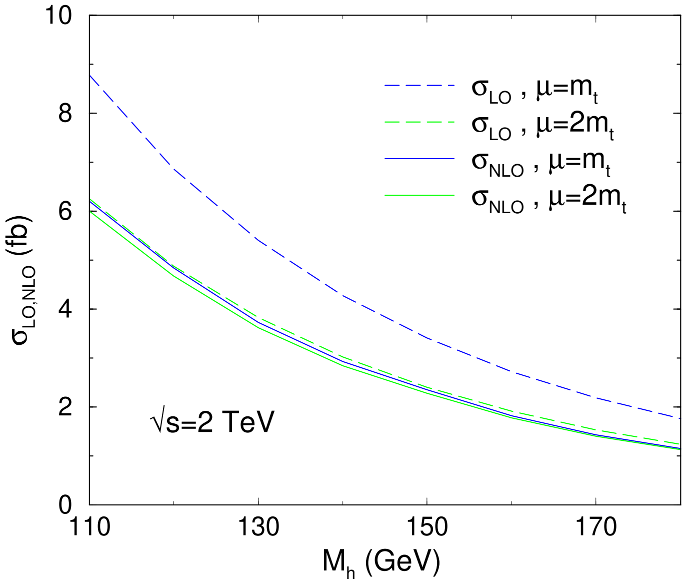


$q\bar{q}, gg \to t\bar{t}H$

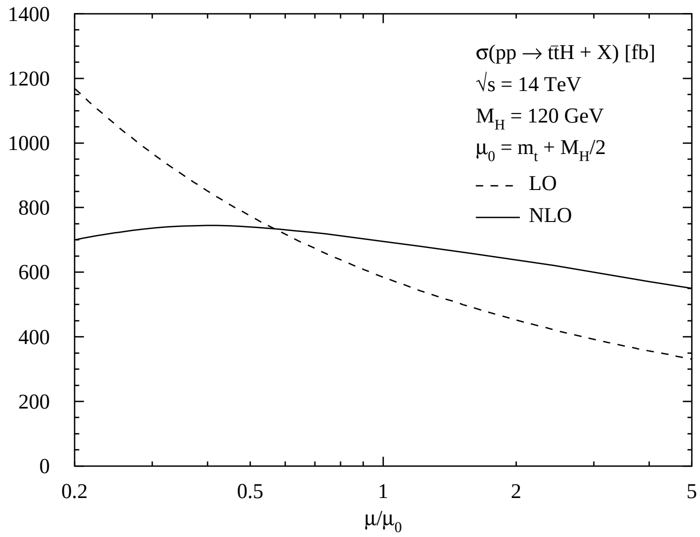
- Cross sections known at NLO of QCD

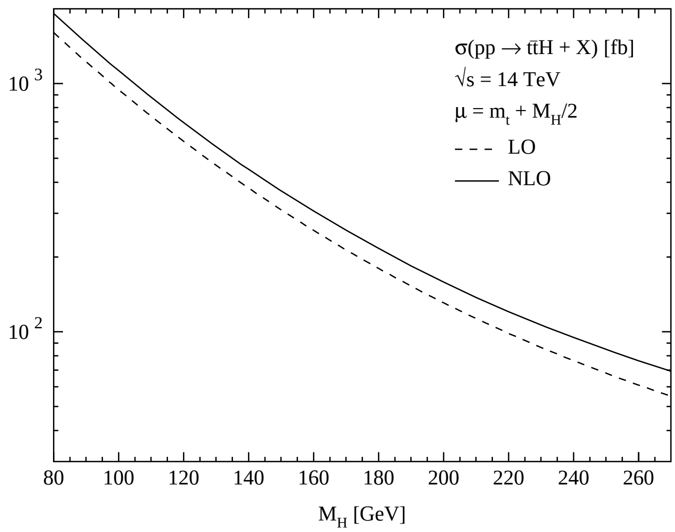
At the Tevatron





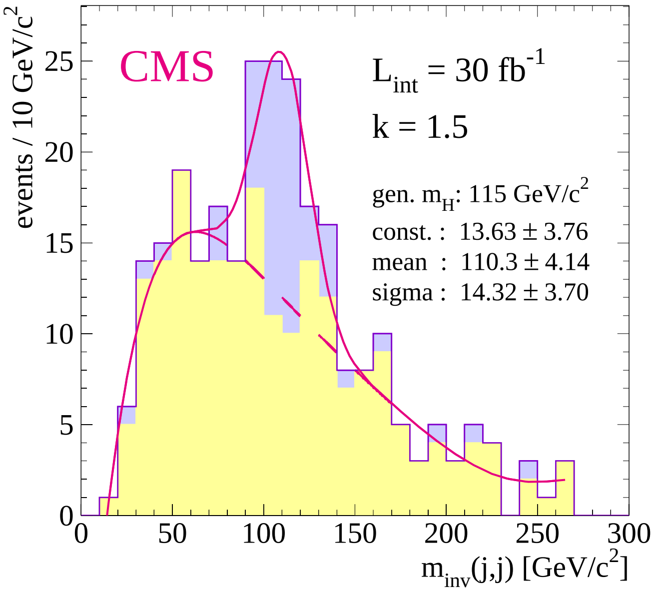
At the LHC





Significant role in discovery at both the Tevatron and the LHC

- Theoretical uncertainty reduced to about 10%
- Small cross section but very neat kinematics: two top quarks in final state

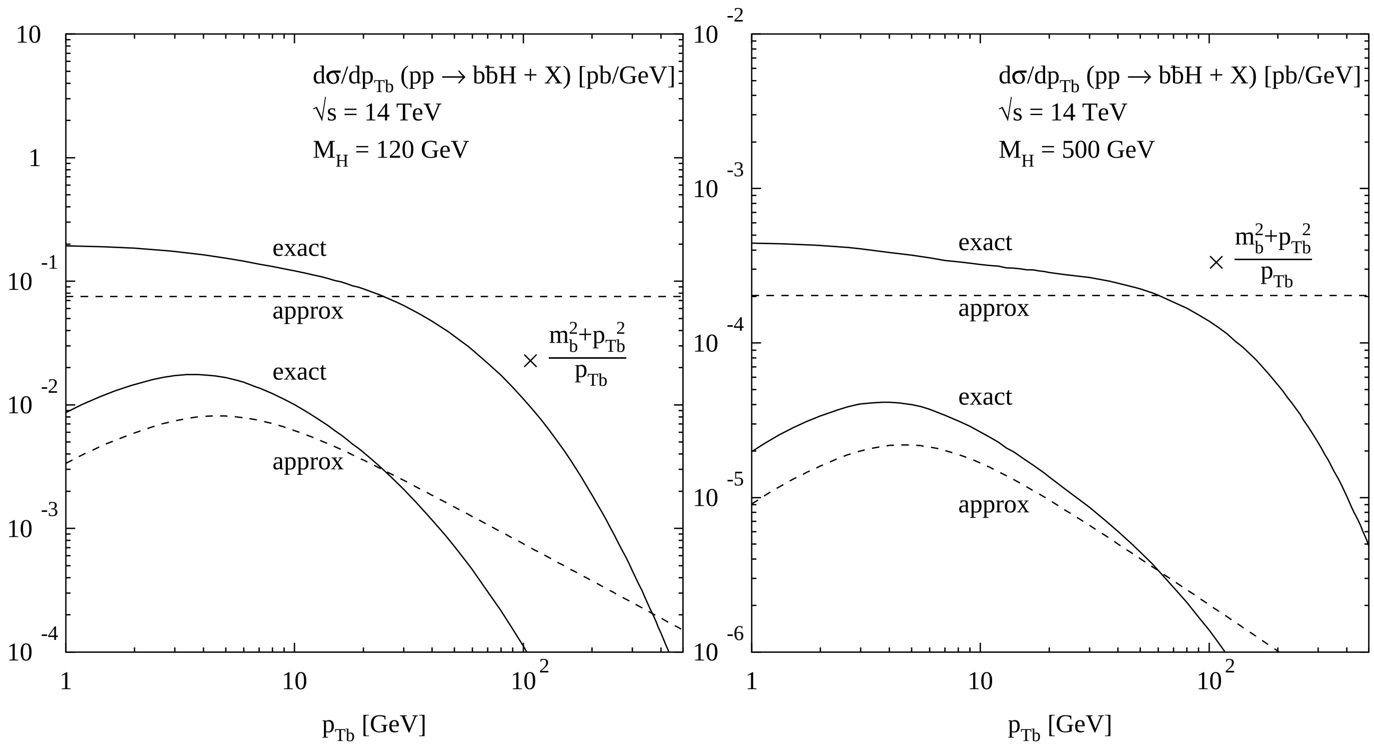


- Instrumental to the measurement if Higgs couplings at the LHC
  - ▷ $t\bar{t}H$, $H \to b\bar{b}, \tau^+\tau^-$ for $M_H \leq 130 - 140$ GeV
  - ▷ $t\bar{t}H$, $H \to WW$ for $M_H \geq 140$ GeV
  - ▷ $t\bar{t}H$, $H \to \gamma\gamma$ requires very high $\mathcal{L}$
- Very important to obtain NLO differential cross sections, in particular for the Tevatron.
- NLO study of the main backgrounds, $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ still missing

$q\bar{q}, gg \to b\bar{b}H$

Where several aspects of QCD are crucial

- At high $\sqrt{s}$ b-quark develop density in the initial state: resum big $\ln(m_b^2/M_H^2)$ in b-quark PDF.
- Perturbative series ordered in Leading and SubLeading powers of $\alpha_s \ln(m_H^2/m_b^2)$
- Need to consider (avoiding double counting)
  - ▷ $b\bar{b} \to H$ (leading)
  - ▷ $bg \to bH$ (sub-leading)
  - ▷ $gg \to b\bar{b}H$ (sub-leading)
- Parton approximation for b-quark need to be tested with full NLO $gg \to b\bar{b}H$



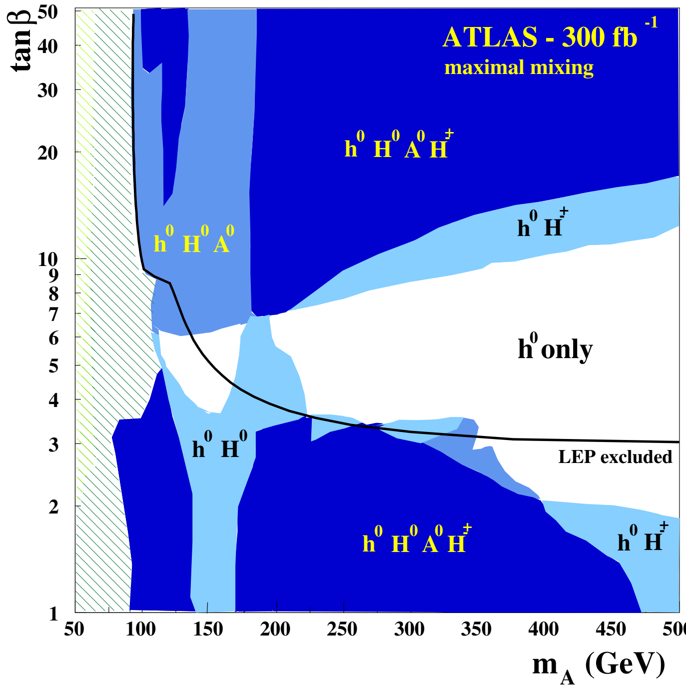
Precision Higgs Physics: the LC

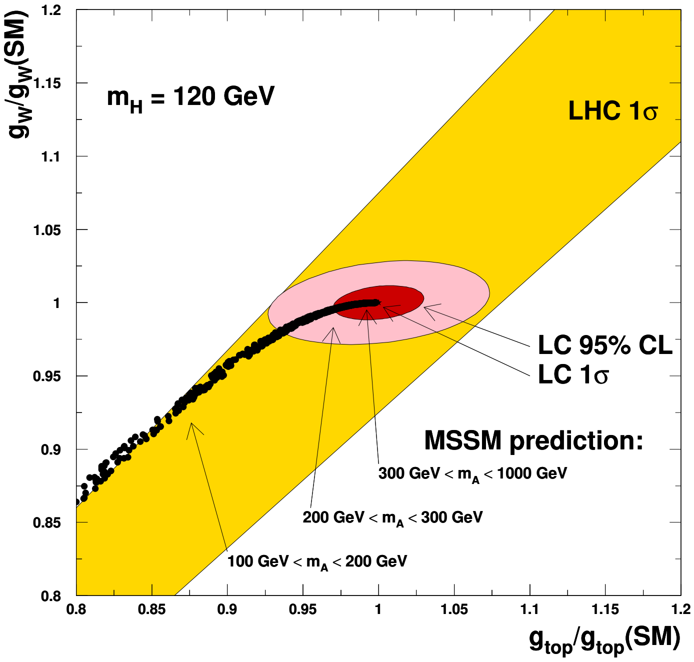
- Look back to e^+e^- Higgs production modes
- Higgs width and couplings can be measured in a model independent way
- Starting at $\sqrt{s} = 350$ GeV: high precisions obtainable

For $M_H = 120$ GeV, $\sqrt{s} = 350, 500$ GeV and 500 fb^{-1}

Decay mode:	$b\bar{b}$	WW^*	$\tau^+\tau^-$	$c\bar{c}$	gg	$\gamma\gamma$
HFITTER (350)	2.4%	5.1%	5.0%	8.5%	5.5%	19%
HFITTER (500)	2.9%	9.3%	7.9%	39%	18%	
Theory	1.4%	2.3%	2.3%	23%	5.7%	2.3%

- Complementary to the LHC in covering the MSSM parameter space





Topics we have not covered ...

- Determination of Higgs properties: mass, spin, parity, ...
- Strong interacting Higgs: equivalence theorem and its consequences
- MSSM full search analysis
- Other possibilities for EW symmetry breaking
- Non-Higgs scalars from New Physics
- Invisible Higgs
- Details on experimental analyses (ask your colleagues!)
- And more ...

Something to think about over Summer!

Some Bibliographical notes

- LEP EW and Higgs working groups:
  - http://lepewwg.web.cern.ch/LEPEWWG/
  - http://lephiggs.web.cern.ch/LEPHIGGS/
- Higgs Physics at the Tevatron: hep-ph/0010338
- Higgs Physics at the LHC:
  - ATLAS Technical Design Report (see Web site)
  - CMS Technical Design Report (see Web site)
  - Summer 2001 studies: hep-ph/0203056,hep-ph/0203187,hep-ph/0203229
- Higgs Physics at the LC:
  - TESLA book: http://www.desy.de/ lcnotes/tdr/
  - LC resource book for Snowmass 2001: hep-ex/0106055-58
- QCD effects in Higgs Physics
  - Review: M. Spira, hep-ph/9705337 and refs. therein
  - Summer 2001 studies: hep-ph/0203056,hep-ph/0203187,hep-ph/0204316 and refs. therein
- Properties of Higgs boson(s):
  - Summer 2001 studies: hep-ph/0203056,hep-ph/0203187,hep-ph/0203123,hep-ph/0205270 and refs. therein