The mysteries of mass and Higgs boson search strategy

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The Standard Model and the Higgs boson

The Glashow-Weinberg-Salam electroweak theory which describes the electromagnetic and weak interactions between quarks and leptons, is a Yang-Mills theory based on the symmetry group $SU(2)_L \times U(1)_Y$. Combined with the $SU(3)_C$ based QCD gauge theory which describes the strong interactions between quarks, it provides a unified framework to describe these three forces of Nature: the Standard Model.

Before introducing the electroweak symmetry breaking mechanism, the model had two kind of fields:

- The matter fields, that is, the 3 generations of left-handed and right-handed chiral quarks and leptons
- The gauge fields corresponding to the spin-one bosons that mediate the interactions.

The matter fields

$$I_f^{3L,3R} = \pm\frac{1}{2}, 0: \quad \begin{array}{lllll} L_1 = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, & e_{R_1} = e_R^-, & Q_1 = \begin{pmatrix} u \\ d \end{pmatrix}_L, & u_{R_1} = u_R, & d_{R_1} = d_R \\ L_2 = \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, & e_{R_2} = \mu_R^-, & Q_2 = \begin{pmatrix} c \\ s \end{pmatrix}_L, & u_{R_2} = c_R, & d_{R_2} = s_R \\ L_3 = \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L, & e_{R_3} = \tau_R^-, & Q_3 = \begin{pmatrix} t \\ b \end{pmatrix}_L, & u_{R_3} = t_R, & d_{R_3} = b_R \end{array}$$

- The left-handed fermions are in weak isodoublets, while the right-handed fermions are weak isosinglets.
- The quarks are triplets under the SU(3)c group, while leptons are color singlets.

The gauge fields

- In the electroweak sector, we have the field B_μ which corresponds to the generator Y of the U(1)Y group and the three fields $W_\mu^{1,2,3}$ which correspond to the generators T^a [with a = 1; 2; 3] of the SU(2)L group.

$$T^a = \frac{1}{2}\tau^a; \tau_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \tau_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \qquad [T^a, T^b] = i\epsilon^{abc}T^c.$$

- In the strong interaction sector, there is an octet of gluon fields $G_\mu^{1,\ldots,8}$ which correspond to the eight generators of the SU(3)C group and which obey the relations

$$[T^a, T^b] = if^{abc}T_c \qquad \mathrm{Tr}[T^aT^b] = \frac{1}{2}\delta_{ab}$$

where the tensor is for f^{abc} is for the structure constants of the SU(3)C group.

The Standard Model Lagrangian without mass terms

The Standard Model Lagrangian, without mass terms for fermions and gauge bosons is given by

$$\mathcal{L}_{\rm SM} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a - \frac{1}{4} W^a_{\mu\nu} W^{\mu\nu}_a - B_{\mu\nu} B^{\mu\nu}$$
$$+ \overline{L}_i i D_\mu \gamma^\mu L_i + \overline{e}_{R_i} i D_\mu \gamma^\mu e_{R_i} + \overline{Q}_i i D_\mu \gamma^\mu Q_i + \overline{u}_{R_i} i D_\mu \gamma^\mu u_{R_i} + \overline{d}_{R_i} i D_\mu \gamma^\mu d_{R_i}$$

where the covariant derivative in the case of quarks is defined as

$$D_\mu \psi = \left(\partial_\mu - i g_s T_a G^a_\mu - i g_2 T_a W^a_\mu - i g_1 \frac{Y_q}{2} B_\mu \right) \psi$$

and the field strenghts are

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f^{abc} G^b_\mu G^c_\nu$$
$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g_2 \epsilon^{abc} W^b_\mu W^c_\nu$$
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

Spontaneous symmetry breaking

- In order to generate masses, we need to break the gauge symmetry in some way; however, we also need a fully symmetric Lagrangian to preserve renormalizability. A posible solution to this dilemma, is based on the fact that it is posible to get non-symmetric results from an invariant Lagrangian.
- A well-known physical example is provided by a ferromagnet: although the Hamiltonian is invariant under rotations, the ground state has the spins aligned into some arbitrary direction.
- In a Quantum Field Theory, the ground state is the vacuum. Thus, the SSB mechanism will appear in those cases where one has a symmetric Lagrangian, but a non-symmetric vacuum.

The Higgs mechanism (1)

- Make use of the Goldsone theorem
- We need to generate masses for the three gauge bosons, W+/- and Z, but not for the photon and QED should stay an exact symmetry.
- The simplest choice is a complex SU(2) doublet of scalar fields

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, Y_\phi = +1$$

- To the SM Lagragian we need to add the invariant terms of the scalar field

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

- For $\mu^2 < 0$, the neutral component of the field Φ will develop a v.e.v.

$$\langle \Phi \rangle_0 \equiv \langle 0 | \Phi | 0 \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}, \text{with} v = \left(-\frac{\mu^2}{\lambda} \right)^{1/2}$$

- We can write the field Φ in terms of four fields $\theta_{1,2,3}(x)$ and *H(x)*

$$\Phi(x) = \begin{pmatrix} \theta_2 + i\theta_1 \\ \frac{1}{\sqrt{2}}(v + H) - i\theta_3 \end{pmatrix} = e^{i\theta_a(x)\tau^a(x)/v} \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v + H(x)) \end{pmatrix}$$

The Higgs mechanism (2)

- By making a gauge transformation on this field in order to move to the unitarity gauge, and then fully expand the term $|D_\mu \Phi|^2$ of the lagrangian, we get the new fields W_μ and Z_μ.

$$W^\pm = \frac{1}{\sqrt{2}}(W^1_\mu \mp iW^2_\mu), \quad Z_\mu = \frac{g_2 W^3_\mu - g_1 B_\mu}{\sqrt{g_2^2+g_1^2}}, \quad A_\mu = \frac{g_2 W^3_\mu + g_1 B_\mu}{\sqrt{g_2^2+g_1^2}},$$

- If we pick-up the terms which are bilinear in the fields *W*, *Z* and *A,* we get

$$M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu + \frac{1}{2} M_A^2 A_\mu A^\mu$$

where the Z and W bosons acquired masses, while the photon is still massles.

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

- The Higgs boson mass can be identified from the part of the Lagrangian containing the Higgs field *H*

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

The Higgs mechanism (3)

One can see that the Higgs boson mass simply reads

$$M_H^2 = 2\lambda v^2 = -2\mu^2$$

- The Feynman rules for the Higgs self interaction vertices are

$$g_{H^3} = (3!) i\lambda v = 3i\frac{M_H^2}{v}, g_{H^4} = (4!) i\frac{\lambda}{4} = 3i\frac{M_H^2}{v^2}$$

and the Higgs boson couplings to fermions and gauge bosons are

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

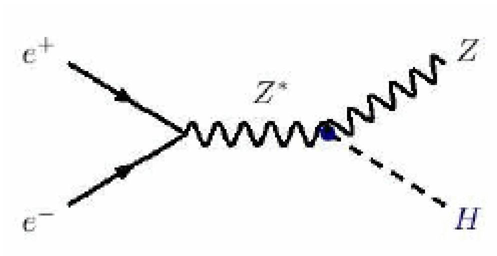
- The v.e.v., *v*, is fixed in terms of the W boson mass or the Fermi constant measured in muon decays.

$$M_W = \frac{1}{2} g_2 v = \left(\frac{\sqrt{2} g^2}{8 G_\mu}\right)^{1/2} \Rightarrow v = \frac{1}{(\sqrt{2} G_\mu)^{1/2}} \simeq 246\mathrm{GeV}$$

Higgs production at lepton colliders

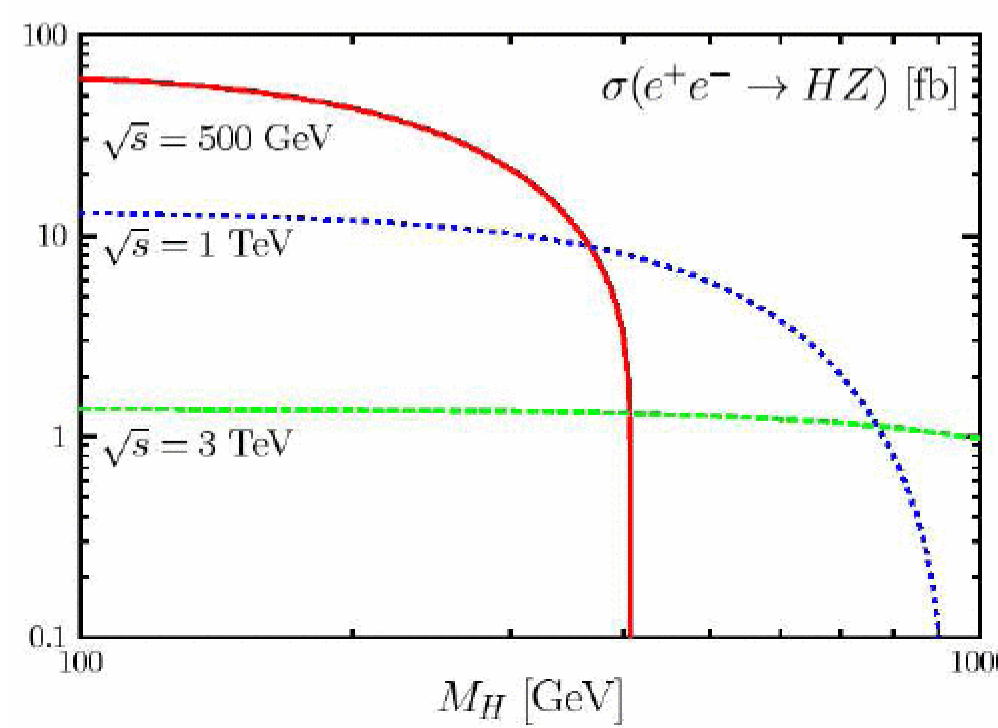
- The e+e- collision is a very simple reaction, with a very well defined initial state and rather simple topologies in the final state.
- It has a favourable signal to background ratio, leading to a very clean experimental environment which allows to easily search for new phenomena and to perform very high precision studies.
- The processes are in general mediated by s-channel photon and Z boson exchanges with cross-sections which scale with 1/s, and t-channel gauge boson or electron/neutrino exchange, with cross-sections wich rise ~log(s).
- The very low cross-sections must be compensated by high accelerator luminosity.
- Main processes for producing Higgs are Higgs-strahlung and the WW fusion mechanism.

The Higgs-strahlung mechanism



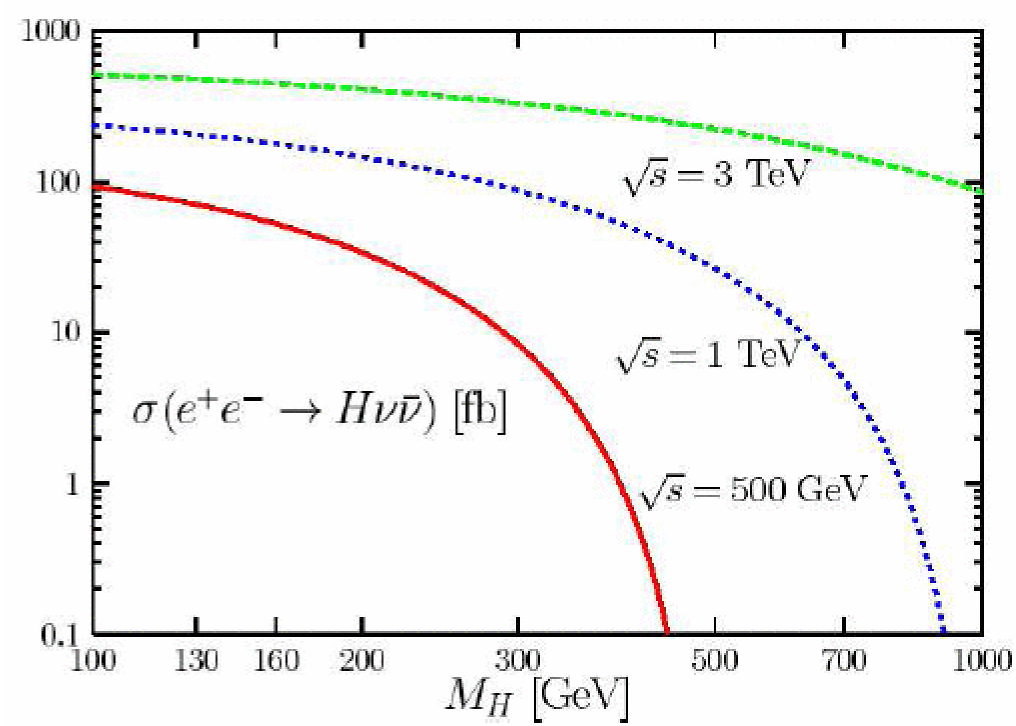
$$\sigma(e^+e^- \to ZH) = \frac{G_\mu^2 M_Z^4}{96\pi s}(\hat{v}_e^2 + \hat{a}_e^2)\lambda^{1/2}\frac{\lambda + 12M_Z^2/s}{(1 - M_Z^2/s)^2}$$

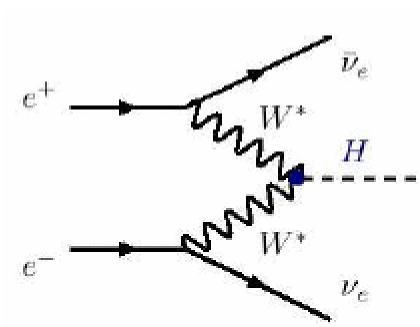
The cross-section of producing Higgs particles in this kind of process goes down for increasing Higgs mass. Also, the probability of detecting Higgs coming from Higgs-strahlung processes decrease fast with the c.m. energy of the e+e- collision.



The WW fusion process

The WW fusion process is most important for small Higgs masses and high c.m. energies.





$$\sigma = \frac{G_\mu^3 M_V^4}{64\sqrt{2}\pi^3} \int_{k_H}^1 dx \int_x^1 \frac{dy}{[1 + (y - x)/\kappa_V]^2} [(\hat{v}_e^2 + \hat{a}_e^2)^2 f(x,y) + 4\hat{v}_e^2 \hat{a}_e^2 g(x,y)]$$

$$f(x,y) = \left(\frac{2x}{y^3} - \frac{1+2x}{y^2} + \frac{2+x}{2y} - \frac{1}{2}\right)\left[\frac{z}{1+z} - \log(1+z)\right] + \frac{x}{y^3}\frac{z^2(1-y)}{1+z}$$

$$g(x,y) = \left(-\frac{x}{y^2} + \frac{2+x}{2y} - \frac{1}{2}\right)\left[\frac{z}{1+z} - \log(1+z)\right]$$

$$\kappa_H = m_H^2/s,\ \kappa_V = M_V^2/s,\ z = y(x - \kappa_H)/(\kappa_V x)$$

Higgs production at hadron colliders

- Unlike lepton colliders, the total cross-section at hadron colliders is very large, approx. 100mb at LHC, resulting in an interaction rate of ~1GHz at the design luminosity.
- The typical cross-sections for producing Higgs are in the most favourable channels less than 100 pb which leads to a very small signal to background ratio.
- In the Standard Model, the main production processes for Higgs particles at hadron colliders, make use of the fact that Higgs boson couples preferentially to the heavy particles.
- According to the production cross-sections, there are 4 main Higgs production mechanisms available in hadron colliders:

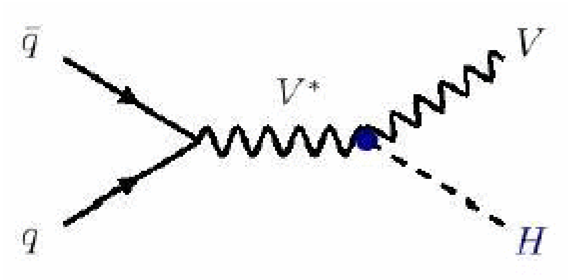
  a) the associated production with W/Z bosons,

  b) the weak vector boson fusion processes,

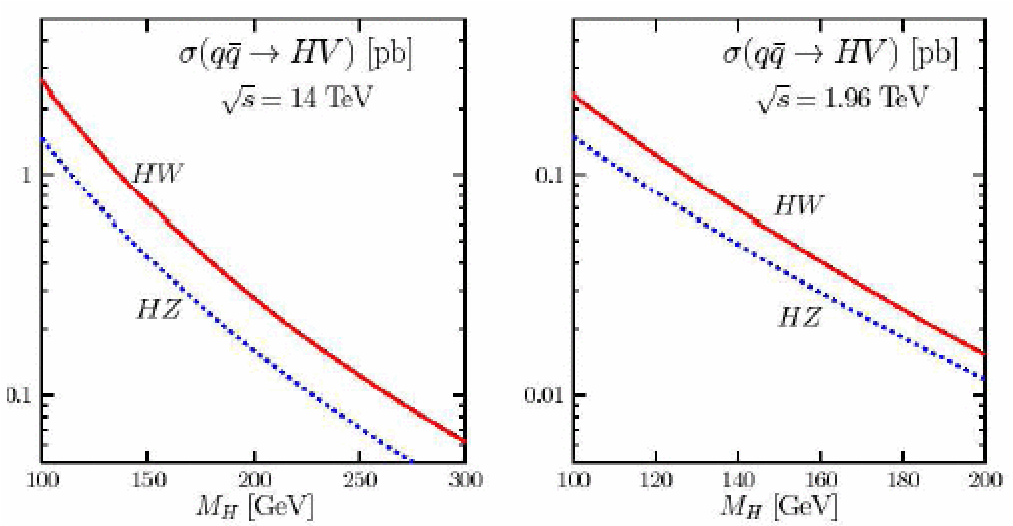
  c) the gluon-gluon fusion mechanism and

  d) the associated Higgs production with heavy top or bottom quarks.

The associated production with W/Z bosons



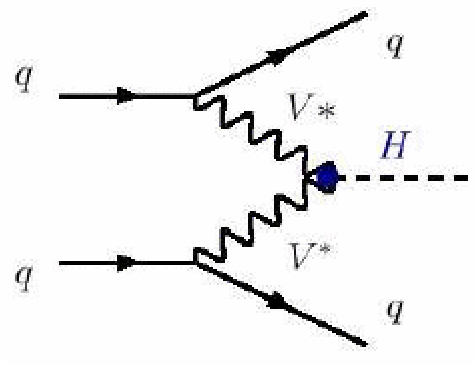
This process can be viewed as the Drell-Yan production of a virtual vector boson, which then splits into a real vector boson and a Higgs particle.

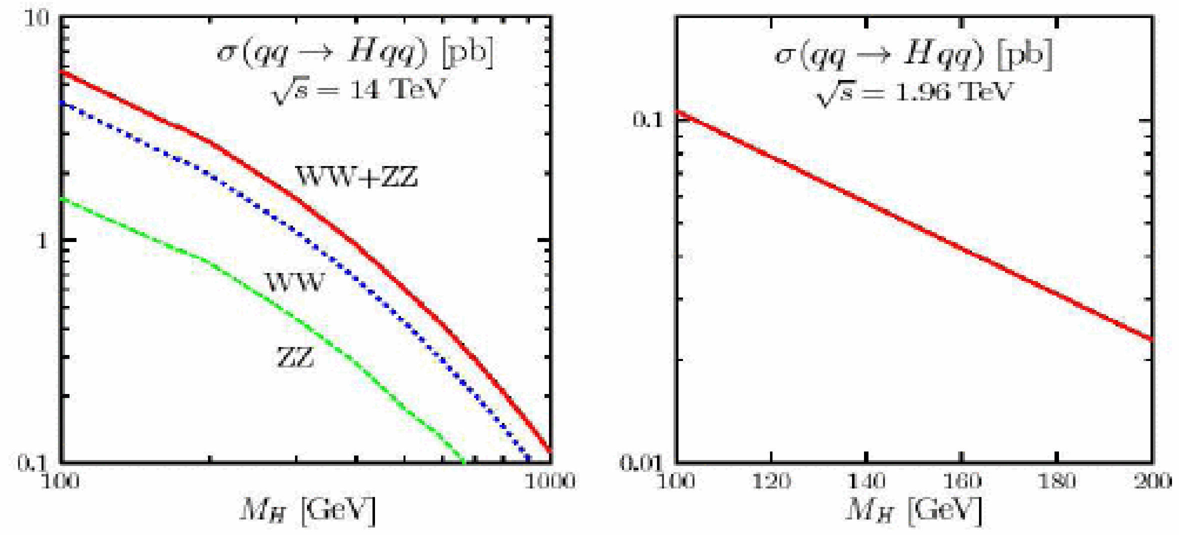


The total production cross sections of Higgs bosons in the strahlung processes at leading order at the LHC(left) and at the Tevatron (right). The MRST set of PDFs have been used.

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

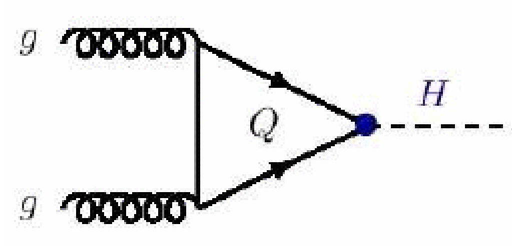
The vector boson fusion process



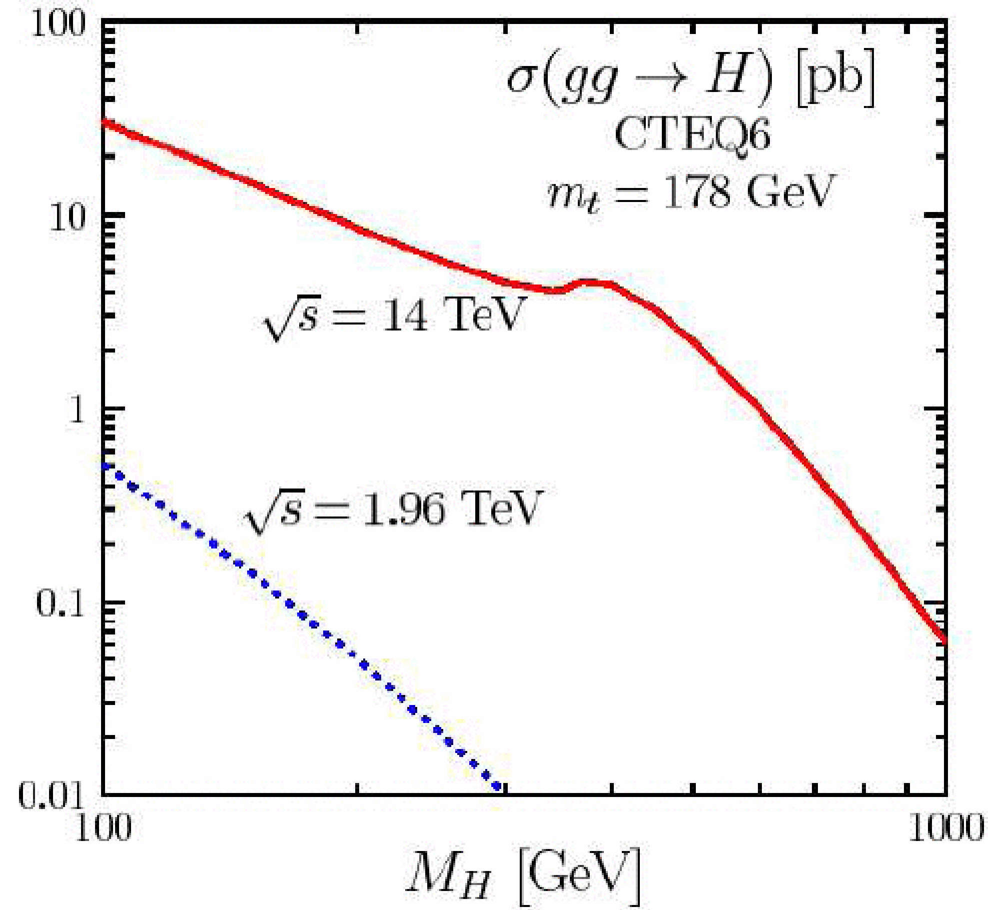


Individual and total cross-sections in the vector fusion process at leading order at the LHC(left) and total cross-section at the Tevatron(right).

The gluon-gluon fusion mechanism

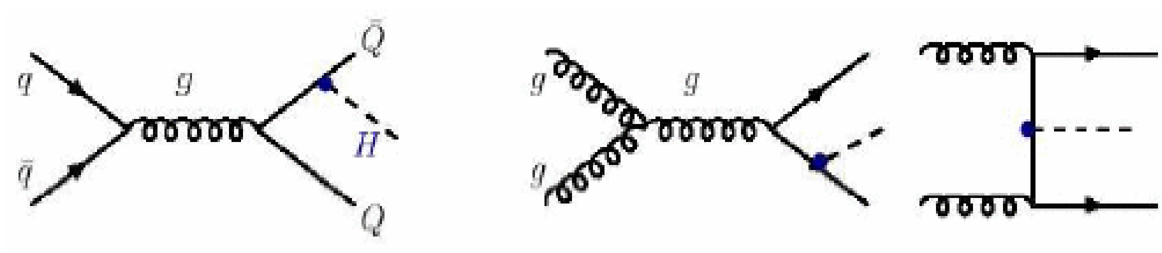


Higgs production in the gluon-gluon fusion mechanism is mediated by triangular loops of heavy quarks. In the SM, only the top quark and, to a lesser extent, the bottom quark will contribute to the amplitude. The decreasing Hgg form factor with rising loop mass is counterbalanced by the linear growth of the Higgs coupling with the quark mass.

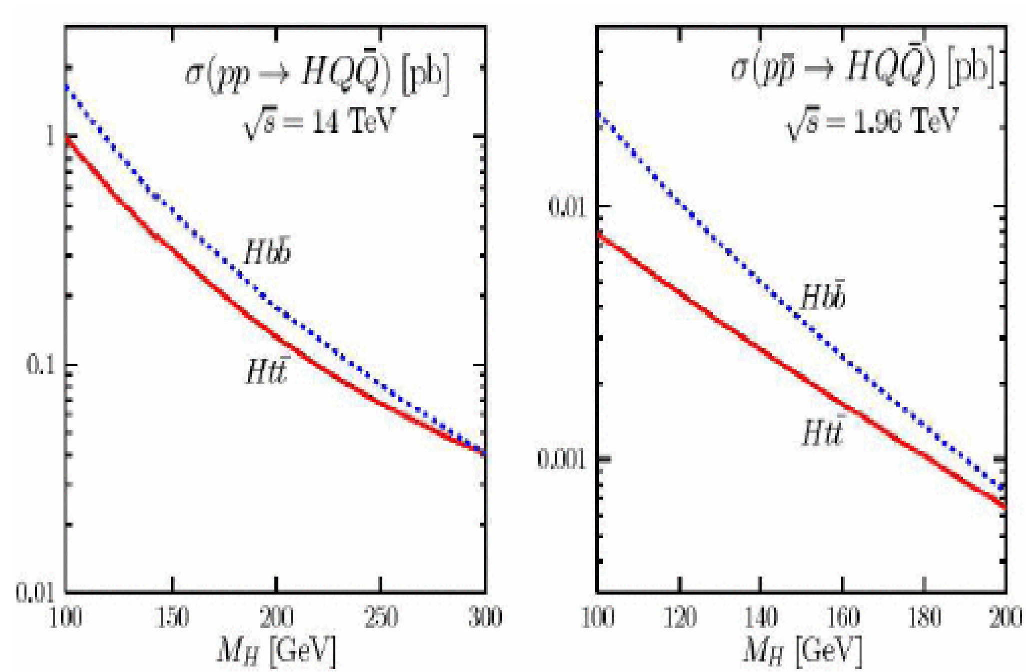


The hadronic production cross-sections for the gg fusion process at LO as a function of mH at the LHC and at Tevatron.

Associated Higgs production with heavy quarks



This process is the most involved of all SM Higgs production mechanisms. At tree level, it originates from qqbar annihilation into heavy quarks with Higgs emitted from the quark lines. At higher energies, the process proceeds mainly through gluon fusion with the Higgs emitted from both the external and internal quark lines.



The ttBarH and bbBarH production cross-sections at the LHC and at the Tevatron.

Higgs decays

The Higgs boson can decay, at tree level, into 2 main channels:

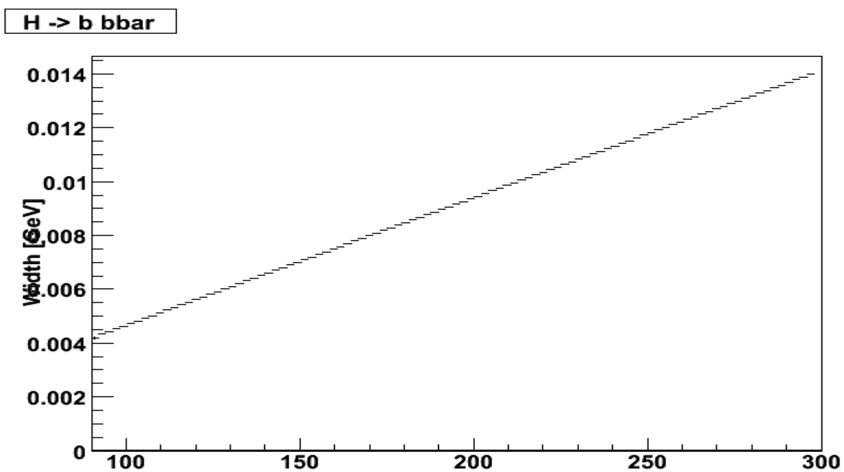
- fermion pairs
- weak gauge boson pairs.

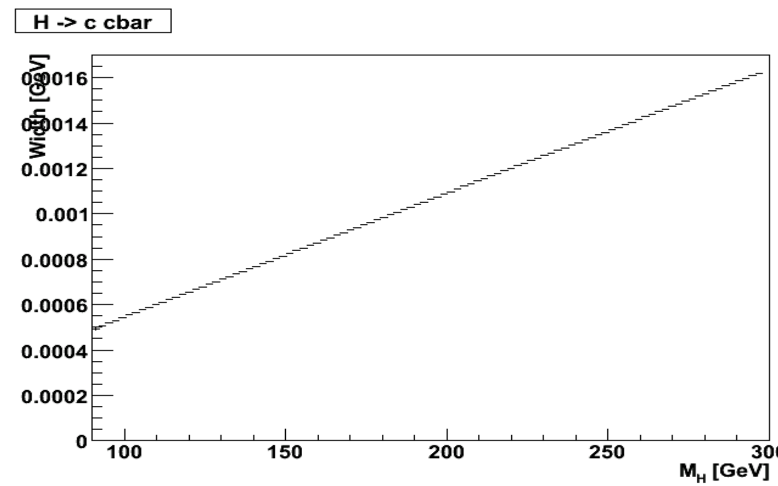
As in the production mechanisms, the Higgs particles will preferentially decay into heavy particles. At low Higgs masses, below WW threshold, the Higgs boson will decay mostly in bottom and charm quark pairs. After the WW threshold, the branching ratios for decays into these low mass channels will drop very fast leaving room only for decays in W, Z and top quark pairs.

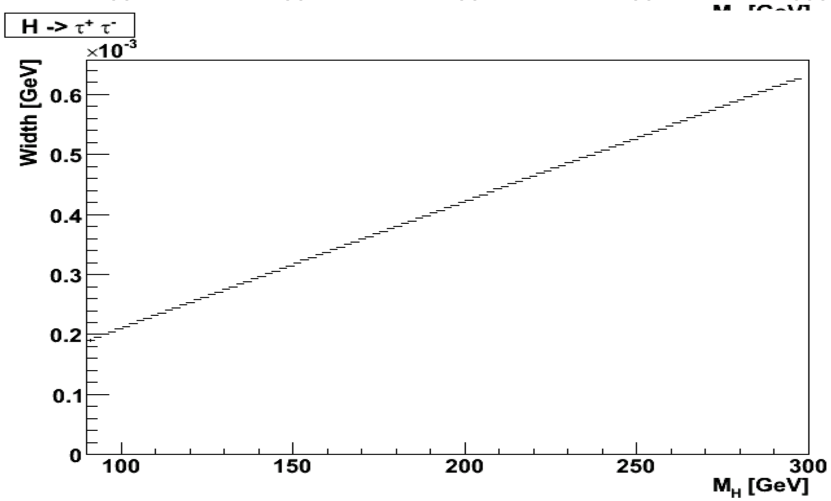
Higgs decay into fermion-antifermion pairs

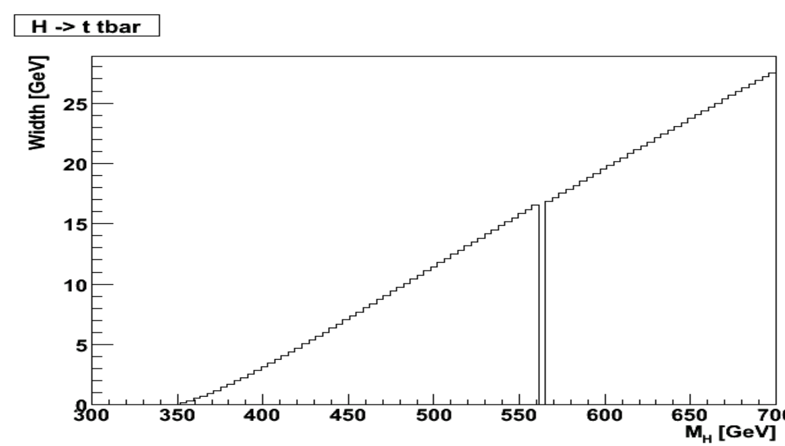
The calculated decay width of Higgs boson into fermion pairs reads as following:

$$d\Gamma = \frac{g^2}{4m_W^2} m_f^2 m_H \left(1 - \frac{4m_f^2}{m_H^2}\right)^{\frac{3}{2}} \frac{d\Omega_1}{32\pi^2} \qquad \Gamma = \frac{g^2}{32\pi} \frac{m_f^2}{m_W^2} m_H \left(1 - \frac{4m_f^2}{m_H^2}\right)^{3/2} \times N_c^f$$





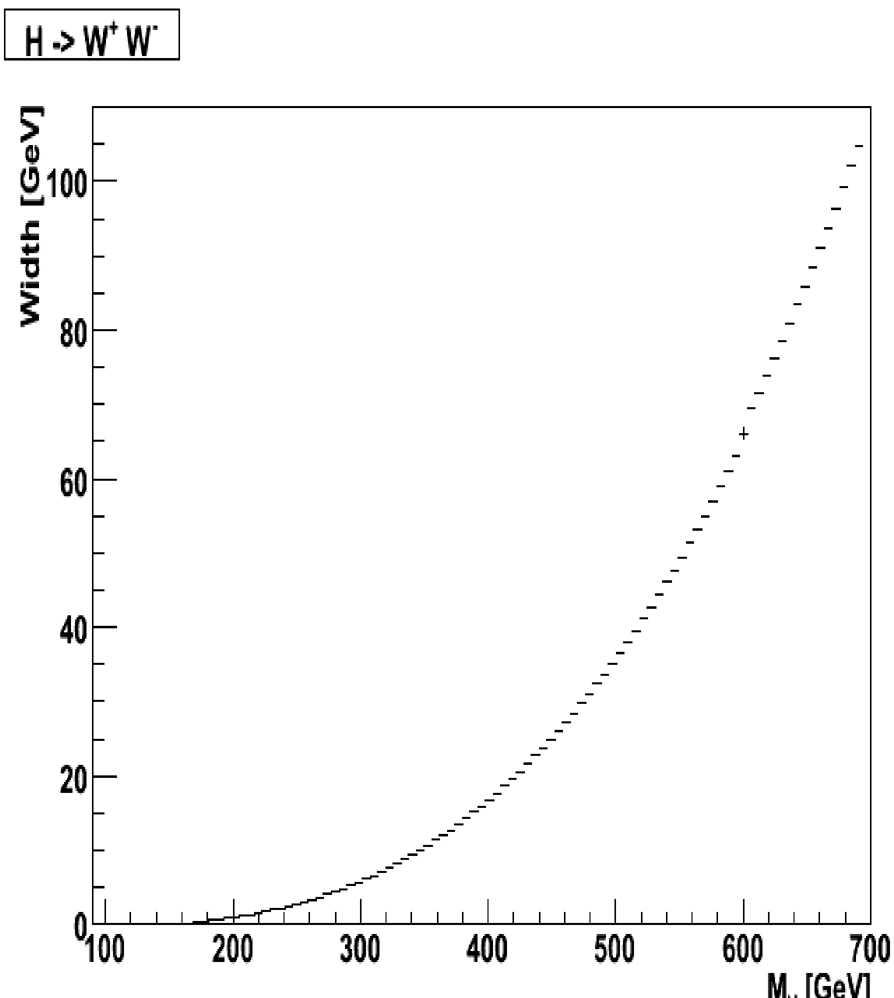


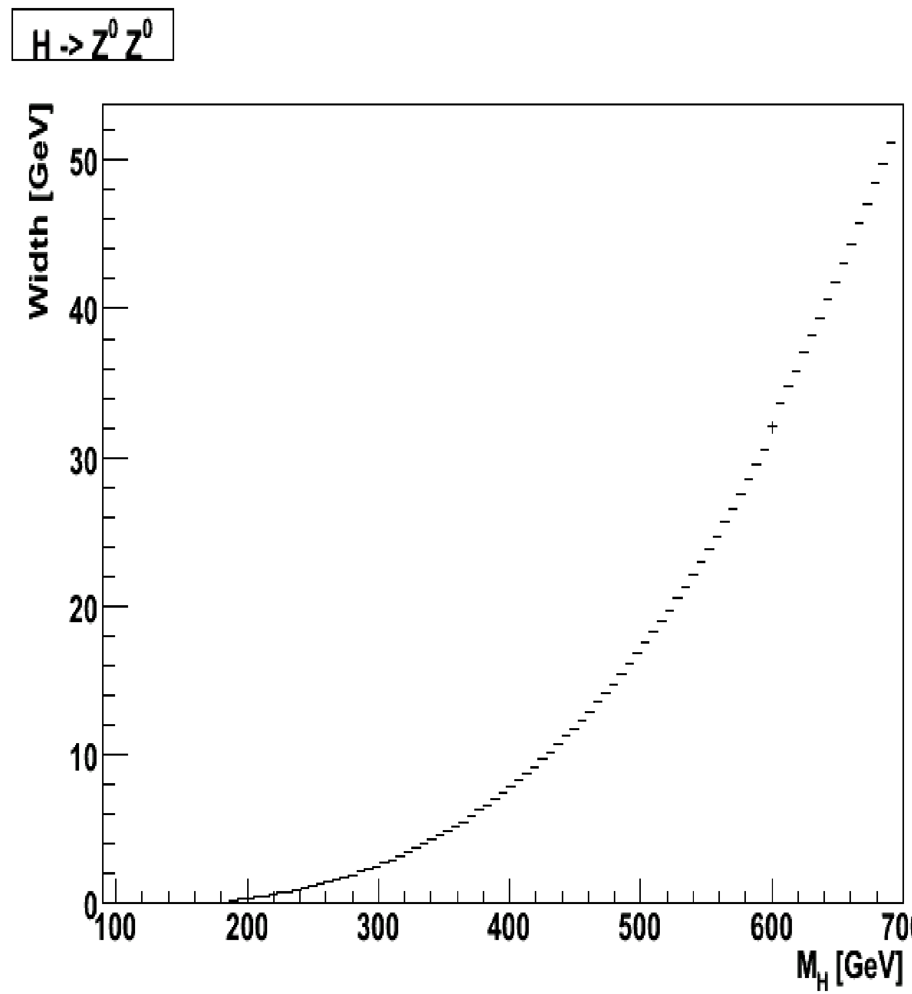


Higgs decay into weak gauge boson pairs

$$\Gamma(H \to W^+W^-) = \frac{G_F}{8\pi\sqrt{2}} m_H^3 \left(1 - \frac{4m_W^2}{m_H^2}\right)^{\frac{1}{2}} \left[3\left(\frac{m_W^2}{m_H^2}\right)^2 - 4\left(\frac{m_W^2}{m_H^2}\right) + 1\right]$$

$$\Gamma(H \to Z^0Z^0) = \frac{G_F}{16\pi\sqrt{2}} m_H^3 \left(1 - \frac{4m_Z^2}{m_H^2}\right)^{\frac{1}{2}} \left[3\left(\frac{m_Z^2}{m_H^2}\right)^2 - 4\left(\frac{m_Z^2}{m_H^2}\right) + 1\right]$$





Higgs search strategy

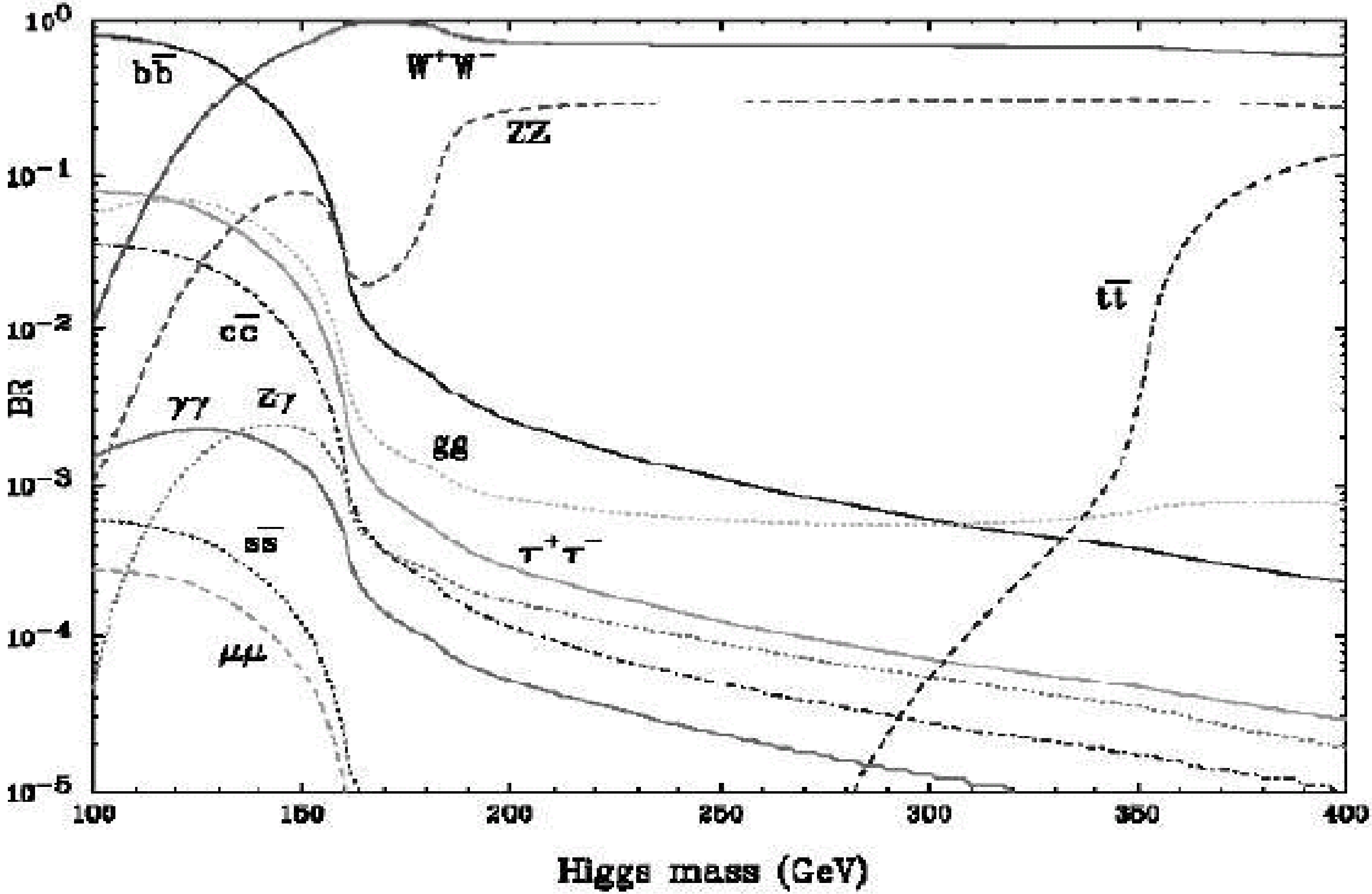
Requirements for a succesful Higgs search strategy:

- Knowledge of the Higgs production mechanisms,
- Knowledge of the Higgs decay channels and branching ratios for different Higgs masses,
- The QCD background processes, which are very abundant, must be estimated in order to improve the signal to background ratio
- Statistics

Depending on the rarity of the final state in which Higgs boson decays with respect to the specific background existing for that particular state, different production mechanisms may be needed on a case-by-case basis.

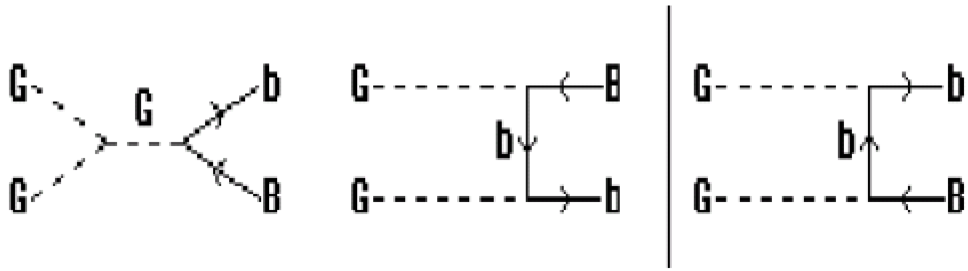
The Higgs search strategy is very dependent on the unknown Higgs mass.

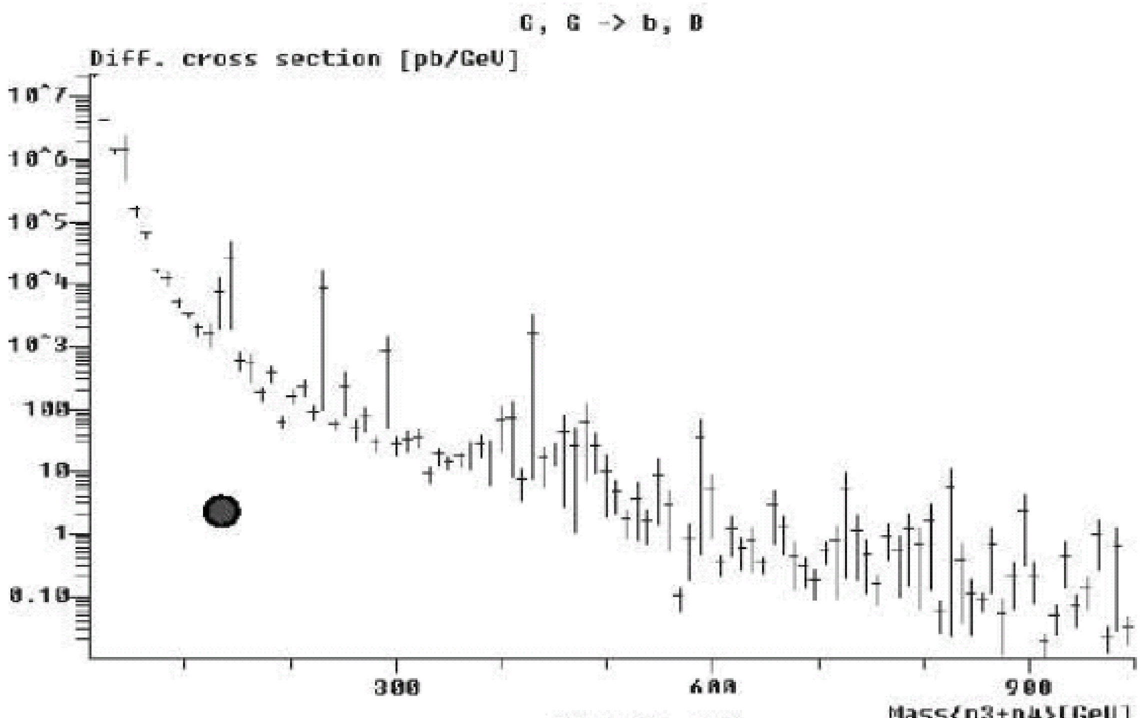
Higgs decay branching ratios



Using the bb-bar decay to discover Higgs

- Its the most probable decay at low Higgs masses.
- There is a strong QCD background coming from “normal” hard scatterings.





M(GeV)

The cross section for all b pair production is shown together with the signal. The signal to background ratio is very small.
We can improve this by considering the Htt production with subsequent H->b+bbar decay.

Beyond the Standard Model

- There are many reasons and opinions why the electroweak theory cannot have the final word. The Standard Model is largely silent on the issue of the origin of the Higgs boson, and this is because the spontaneous breaking of the electroweak SU(2)xU(1) symmetry is postulated in the model by the device of introducing a potential of scalar fields, V, constructed just so that it can lead to such a breaking.
- The Higgs boson is necessary to regulate the *s*-growth of the amplitudes, otherwise the unitarity would be violated unless some new physics will appear.
- If a Higgs boson can be found in future experiments with a relatively small mass, say $M_H < v = 246\ GeV$, then we are in the weakly coupled regime and the theory remain consistent.
- However, if the Higgs boson is too heavy, terms of higher order become increasingly more important and will get out of control, and the perturbative approach loses its usefulness.