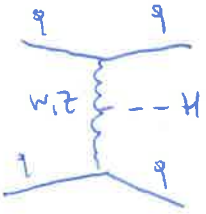
WEAK BOSON FUSION (VBF)



Weak boson fusion is the second important production channel of the SM Higgs boson at the LHC, and it has several distinctive features. It has the largest cross section among the processes that occur at tree-level to lowest order, and it has a distinctive signature of two forward jets, which makes it possible to tag them and to study Higgs boson decays that are normally difficult to be isolated, like $H \to \tau\tau$.

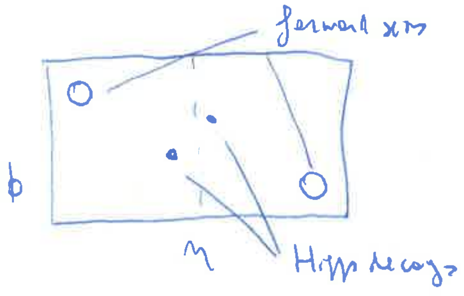
The process occurs through the scattering of two quarks, that exchange a W or a Z boson, which in turn radiates the Higgs boson. When we pick up two valence quarks from the proton their PDF is peaked at $x \sim 0.1-0.2$. The outgoing quarks, after exchanging the vector boson will have a transverse momentum of the order of a fraction of the vector boson mass. This means that this process tends to produce two highly energetic jets with a large rapidity interval between them.

This conclusion can also be reached by noting that if p_i and p_j are the momenta of the incoming and outgoing quarks say in the upper part of the diagram, there is a propagator factor $\frac{1}{Q^2-m_V^2}$ for the vector boson with $Q^2=(p_i-p_j)^2<0$.

The suppression is smaller if Q^2 is smaller but

$$Q^2=(p_i-p_j)^2=-2p_ip_j=-2E_iE_j(1-\cos\theta)\approx -E_i^2(1-\varepsilon)\theta^2$$

where ε is the fraction of the quark momentum carried away by the vector boson. We conclude that the amplitude is larger when θ is smaller, and that the two outgoing quarks end up in the forward region of the detector, whereas the Higgs decay products will generally go central



Another distinctive feature of VBF is QCD radiation.

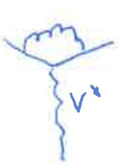
Beyond the lowest order the additional jet activity comes from radiations off the quarks, and is thus typically forward. By contrast, the major backgrounds, like $t\bar{t}$, will involve QCD radiation between the incoming partons, and thus the central region is usually covered. Central jet activity can be vetoed, thus leading to a good background rejection.

Radiative corrections to VBF are known at the NLO (QCD+EW) and NNLO QCD (neglecting color connections between the scattered quarks), and are generally small, thus this channel is a very good candidate for precision studies.

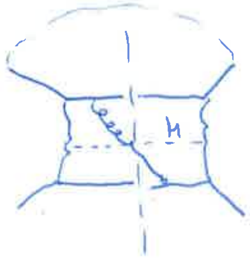
One important point is that the genuine VBF process is in principle not unambiguously defined, since one has to consider also the gluon fusion contribution to H+2 jets.

Nevertheless there are variables which are sensitive to the production mechanism. The first is the azimuthal separation of the tagging jets, which has a rather different shape in ggF and VBF, and the other is the rapidity of the third jet with respect to the average of the two tagging jets (the "Zeppenfeld variable"), which, due to the very peculiar radiation pattern in VBF, is completely different from what we see in H+2 jets from gluon fusion.

We now discuss the computation of QCD radiative corrections at NLO. They consist of virtual and real emission diagrams

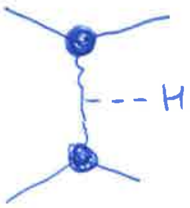


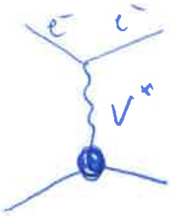
however there are no diagrams with gluons connecting the upper and lower part



a diagram like this would in fact vanish due to color conservation

This implies that NLO QCD corrections for VBF can be obtained by using the STRUCTURE FUNCTION approach, in which one can directly apply the well known results from Deep Inelastic Scattering





The NLO calculation gives corrections of $O(5\%)$ which are partially compensated by the EW corrections. NLO QCD+EW calculations are available in the VBFeNLO and HAWK programs

In summary, the VBF process has a smaller cross section than ggF, but it provides a rather clean environment, with theoretical predictions under very good control (Recently also NNLO corrections have been computed in the structure function approach: the effect is at the 1% level).

VBF can thus be used for precision studies of the Higgs boson properties when enough luminosity will be accumulated.

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"ZEPPENFELD VARIABLE"

↓

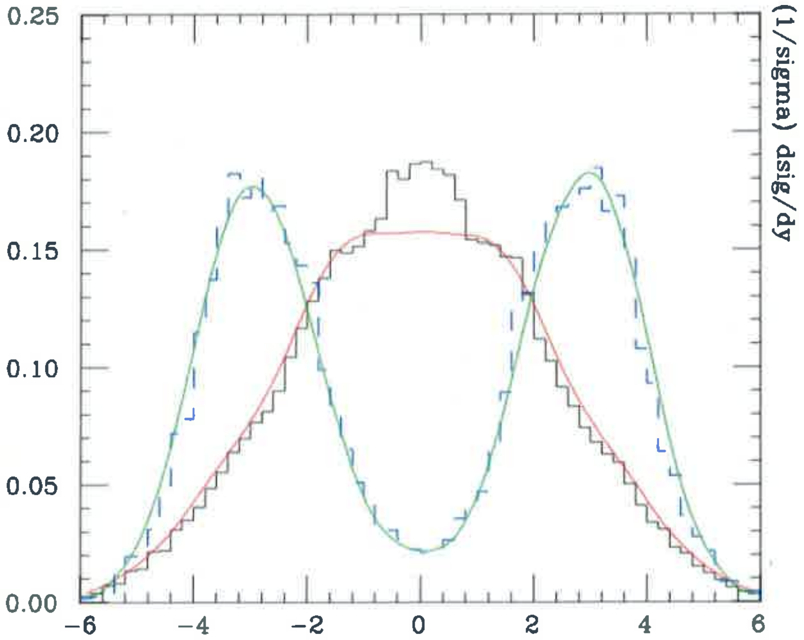

Figure 7: Normalised distribution of the rapidity of the third jet, measured with respect to the rapidity average of the two tagging jets in Higgs + 3 parton events after the parton shower, via gluon fusion (solid) and via VBF (dashed histogram). Also shown are the pure parton level expectations, generated with Higgs + 3 parton matrix elements, for gluon fusion (red curve) and VBF (green curve).

$y_3 - \frac{y_1+y_2}{2}$

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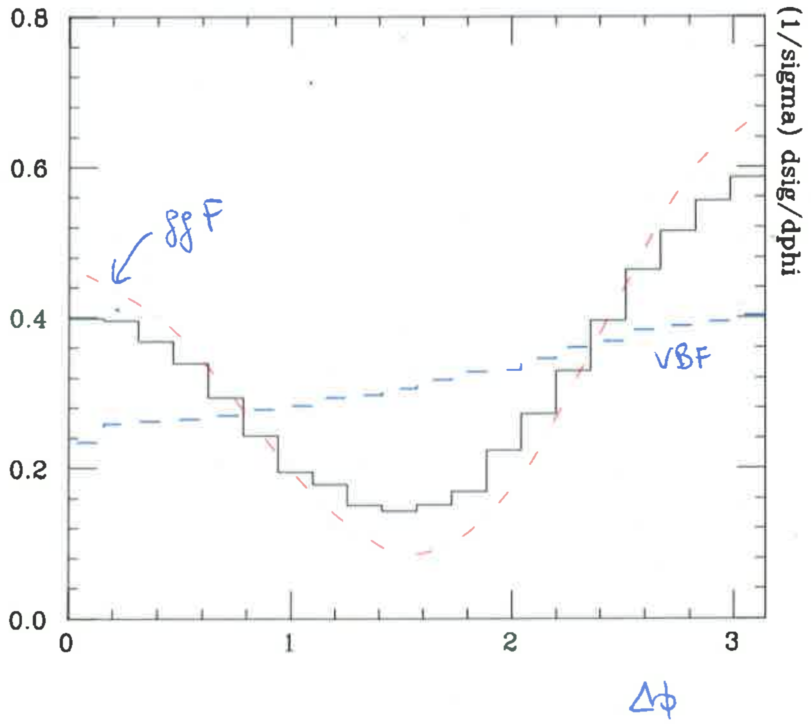
AZIMUTHAL SEPARATION OF THE TAGGING JETS



The matrix element squared $|M_{qq\to qqH}|^2$ in the forward scattering region is proportional to m_{jj}^2 and it is thus roughly independent on $\Delta\phi$ ⇒ the $\Delta\phi$ distribution for VBF is thus rather flat.

In the case of gg fusion, the matrix element squared becomes proportional to $\underline{p}_{T_1} \cdot \underline{p}_{T_2}$

⇒ The cross section is strongly suppressed at $\Delta\phi \sim \frac{\pi}{2}$

↓
see
hep-ph/0105325

①

VH

The associated production of the Higgs boson with a vector boson is the third channel as far as the cross section is concerned at the LHC, while it was the most important channel at the Tevatron, where its cross section is larger than the VBF cross section for a light Higgs. This is due to the fact that in $p\bar{p}$ collisions $q\bar{q} \to VH$ can proceed through two valence quarks, which carry more momentum with respect to the sea quarks on average.

At the lowest order VH production $(V = W^{\pm}, Z)$ proceeds as a Drell-Yan process, where the off shell vector boson V^* radiates the Higgs boson.

The inclusive cross section can be obtained from the $e^+e^- \to VH$ cross section by using the appropriate couplings to the quarks and adding a factor $\frac{1}{3}$ to average over the number of colors:

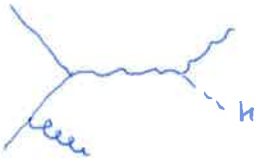
$$\hat{\sigma}_{LO}^{VH}(\hat{s}) = \frac{G_F^2 m_V^4}{288\pi \hat{s}^2} \left(v_q^2 + a_q^2\right) \lambda^{1/2}(m_V^2, m_H^2, \hat{s}) \; \frac{\lambda(m_V^2, m_H^2, \hat{s}) + 12\hat{s} m_V^2}{(s - m_V^2)^2}$$

The total hadronic cross section is obtained through the factorization theorem as

$$\sigma_{LO}^{VH} = \sum_{a,b = q_j, \bar{q}'_j} \int_0^1 dx_1 dx_2 \, f_a(x_1, M_F^2) \, f_b(x_2, M_F^2) \, \sigma_{LO\,ab}^{VH}(x_1 x_2 s)$$

The cross section with WH final states $(W = W^+ + W^-)$ is typically a factor of 2 larger than the one with ZH final states.

Since the VH final state is colorless, the NLO corrections to VH production are identical to those of the Drell-Yan process



By writing

$$\sigma^{VH} = \sum_{a,b} \int_0^1 dx_1 dx_2 dz\, f_a(x_1,\mu_F^2)\, f_b(x_2,\mu_F^2)\, \hat{\sigma}_{ab}^{VH}(z, \alpha_s(\mu_R^2), \mu_R, \mu_F)$$

we have

$$\hat{\sigma}_{ab} = \sum_{c,d=q_j\bar{q}_{j'}} \hat{\sigma}_{LO\,c,d}(x_1 x_2 z s) \left(\delta(1-z)\,\delta_{ac}\delta_{bd} + \frac{\alpha_s(\mu_R)}{\pi}\, g^{(1)}_{ab}(z;\mu_F,\mu_R) + \cdots \right)$$

where

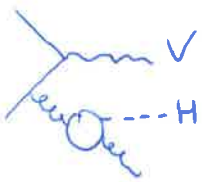
$$g^{(1)}_{q\bar{q}} = P_{qq}(z) \log\frac{M^2}{\mu_F^2} + C_F\left[\left(\frac{\pi^2}{3}-4\right)\delta(1-z) + 2(1+z^2)\,D_1(z)\right]$$

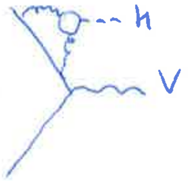
$$g^{(1)}_{gq} = \frac{1}{2} P_{qg}(z) \log\frac{(1-z)^2 M^2}{\mu_F^2} + \frac{1}{8}(1+6z-7z^2)$$

$$g^{(1)}_{gg} = 0 \qquad P_{qq} = C_F\left(\frac{1+z^2}{1-z}\right)_+ \qquad P_{qg} = \frac{1}{2}\left(z^2+(1-z)^2\right)$$

The above coefficient functions, which are the same entering in the NLO corrections to the Drell-Yan process, are completely analogous to the corrections we have evaluated for $gg \to H$ (just in the $q\bar{q}$ channel instead of the gg channel) $K_{NLO} \sim 1.3$

At NNLO, besides the corrections of Drell-Yan type, one has to consider additional diagrams mediated by a heavy quark loop





These diagrams contribute to the 1-3 % level.

When $V=Z$ there are other non Drell-Yan like diagrams induced by gg fusion

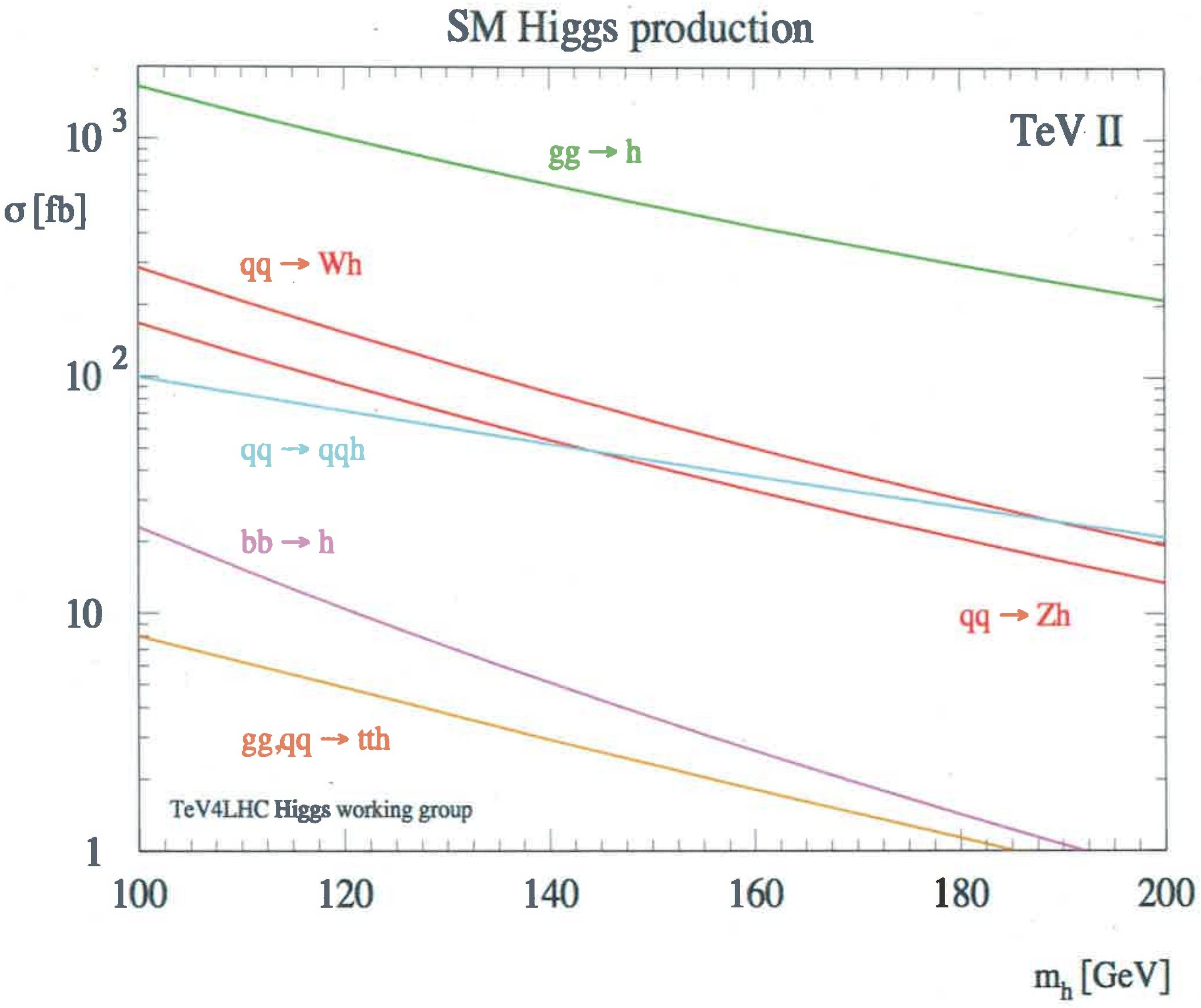
These contributions are at the few percent level on the total cross section.

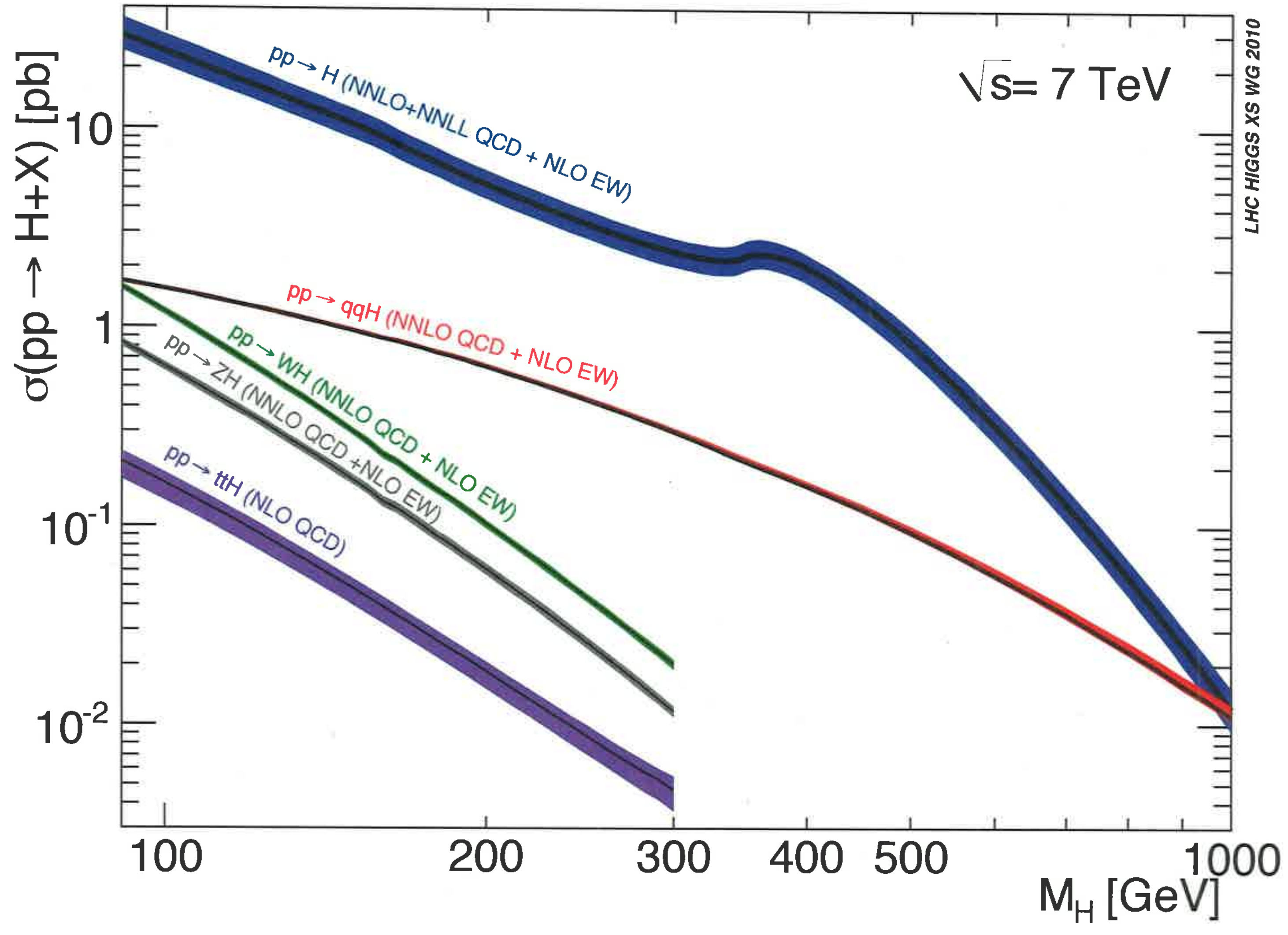
At the Tevatron the VH channel was the most important for a light Higgs, because the lepton(s) from the V decay provides the necessary background rejection, and because the $H \to \gamma\gamma$ decay mode offers too small a rate to be observed.

At the LHC the situation is different, and this channel has been considered for many years too difficult to be observed, due to the large backgrounds.

The $t\bar{t}$ background can easily mimic a $W b\bar{b}$ signal if one of the W from the top decay go in the beam direction. Moreover, in the decay of a top quark at rest ($t \to Wb$) the energy of the b quark is about 65 GeV*, and thus rather close to $m_H/2$. Another issue is that the relatively small typical invariant mass of the VH pair ($M_{HV} \gtrsim 200$ GeV) implies that the system is produced at medium rapidities (Remember that $Y_{max} = \frac{1}{2} \ln \frac{M^2}{s}$!), thus a certain fraction of events is lost because the V and H decay products go beyond the rapidity coverage of the detector. The idea proposed by Butterworth et al. (2008) was to study the process at high transverse momenta. In this region the cross section (say for $p_{TH} > 200$ GeV) is only about 5 % of the inclusive cross section, but there are several advantages. The high p_T implies that M_{HV} is large, and thus the HV system is more central. The V and H decay products will have sufficiently large p_T to be tagged. The background is under better control because, for example, it is impossible for a $t\bar{t}$ event to produce a high p_T $b\bar{b}$ system and a leptonically decaying W without a jet recoiling. Moreover, a high p_T Higgs decaying into a $b\bar{b}$ pair gives two b-jets which are rather collimated (fat jet). This proposal has essentially resurrected the VH channel at the LHC.

* $E_b \simeq \dfrac{m_t^2 - m_W^2 + m_b^2}{2 m_t}$ two body decay


SM Higgs production
σ [fb]
10 3
10 2
10
1
TeV II
gg → h
qq → Wh
qq → qqh
bb → h
qq → Zh
gg,qq → tth
TeV4LHC Higgs working group
100
120
140
160
180
200
m_h [GeV]


σ(pp → H+X) [pb]
10
1
10^-1
10^-2
100
200
300
400
500
1000
M_H [GeV]
√s= 7 TeV
LHC HIGGS XS WG 2010
pp→ H (NNLO+NNLL QCD + NLO EW)
pp→ qqH (NNLO QCD + NLO EW)
pp→ WH (NNLO QCD + NLO EW)
pp→ ZH (NNLO QCD +NLO EW)
pp→ ttH (NLO QCD)