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# Prospects for Higgs search at LHC

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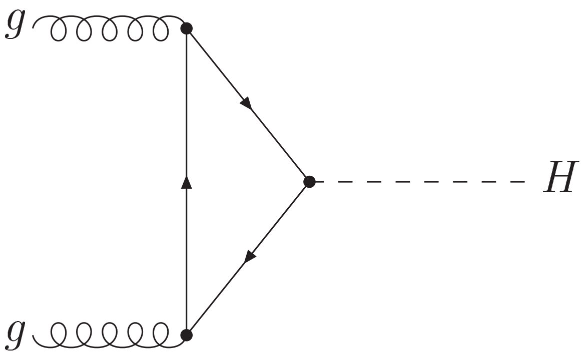
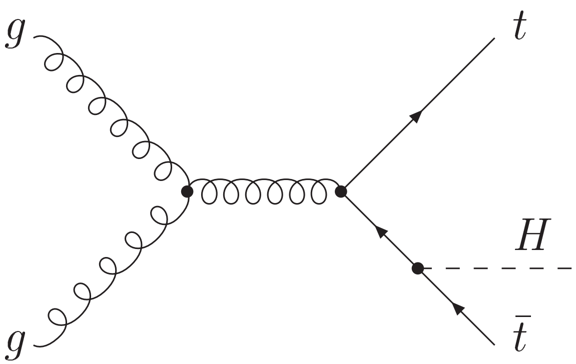
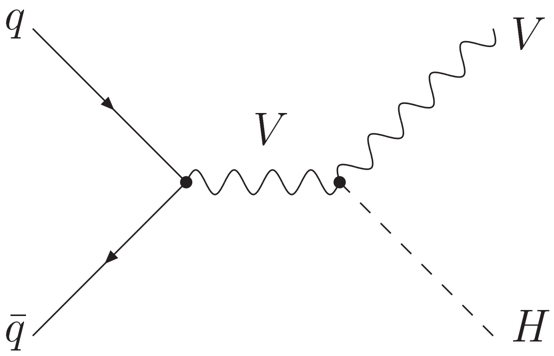
*many thanks to F. Gianotti, K. Jakobs, M.L. Mangano, G. Montagna and M.T. Zeyrek*

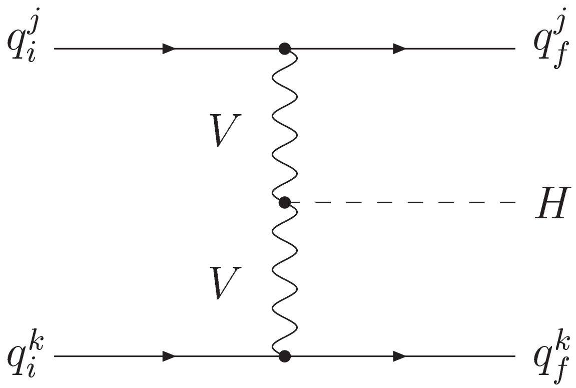
ICHEP02 Amsterdam, 25 July, 2002

# SM Higgs production at LHC

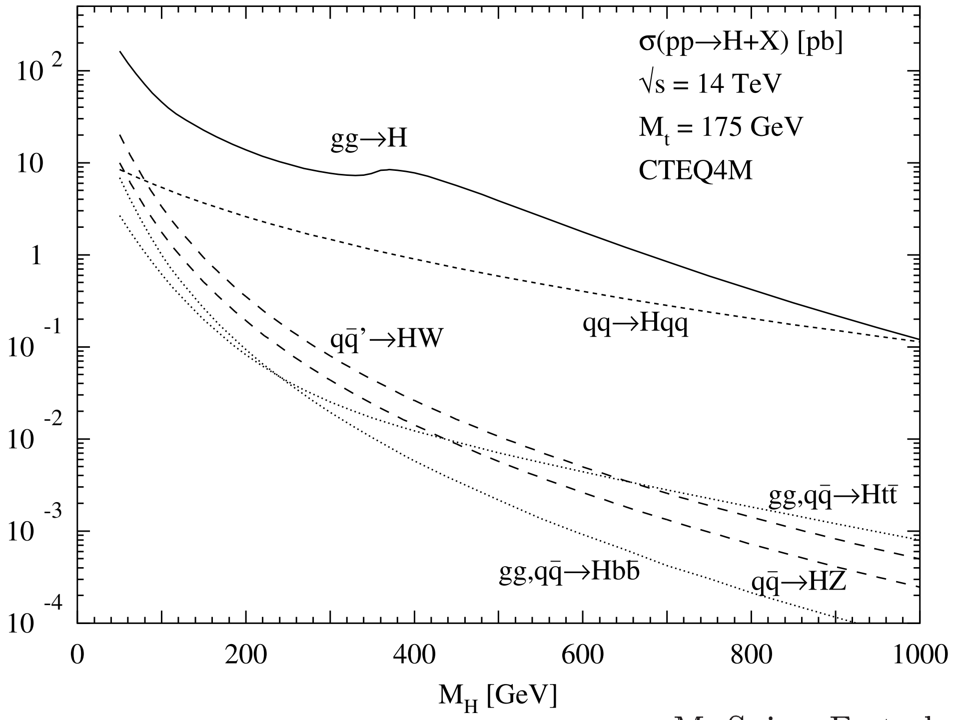


## Signal sections at LHC ($\sqrt{s} = 14$ TeV)




M. Spira, Fortschr. Phys. 46 (1998) 203

Understand uncertainties in the theoretical predictions important to disentangle a Higgs boson signal from the background

At present NLO corrections for all the Higgs production channels of interest at hadron colliders have been completed with attempts beyond NLO (NNLO calculation for $gg$ fusion in the limit of heavy top quark)

R. Harlander and W. Kilgore Phys. Rev. Lett. 88 (2002) 201801

# Associate production $pp \to t\bar{t}h$

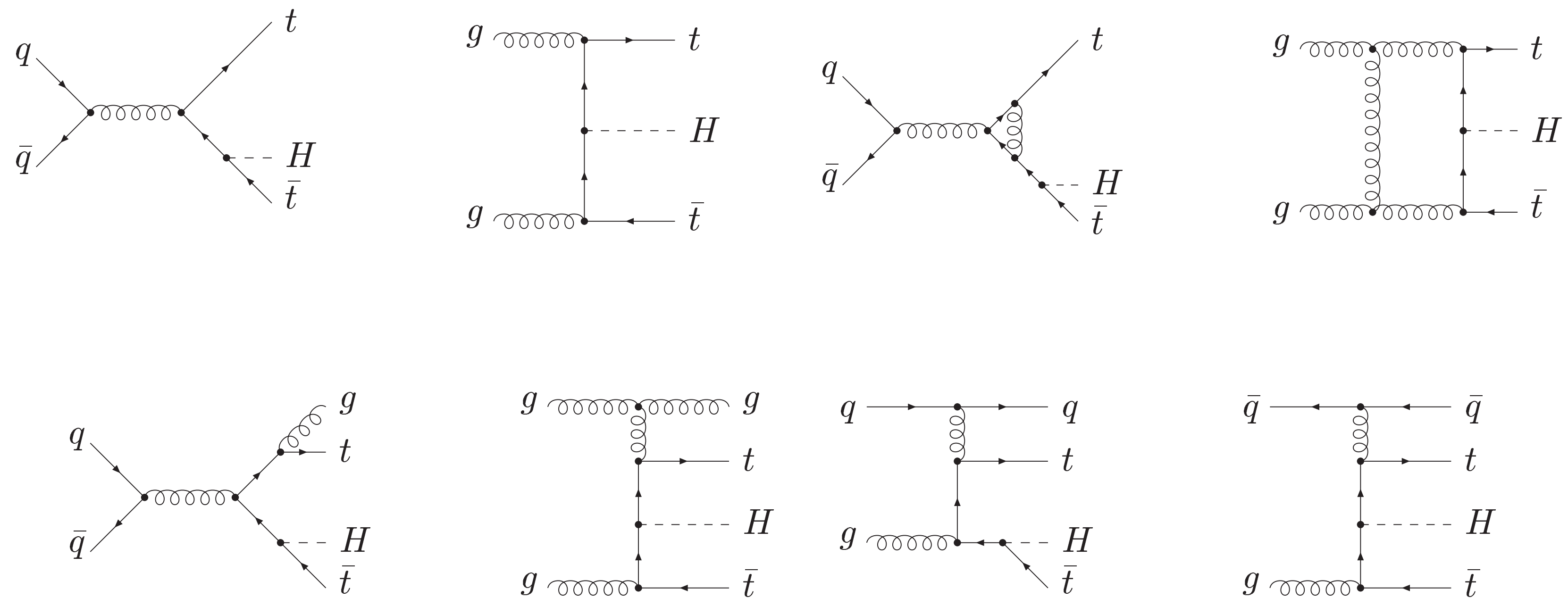
The NLO QCD corrections have been recently calculated

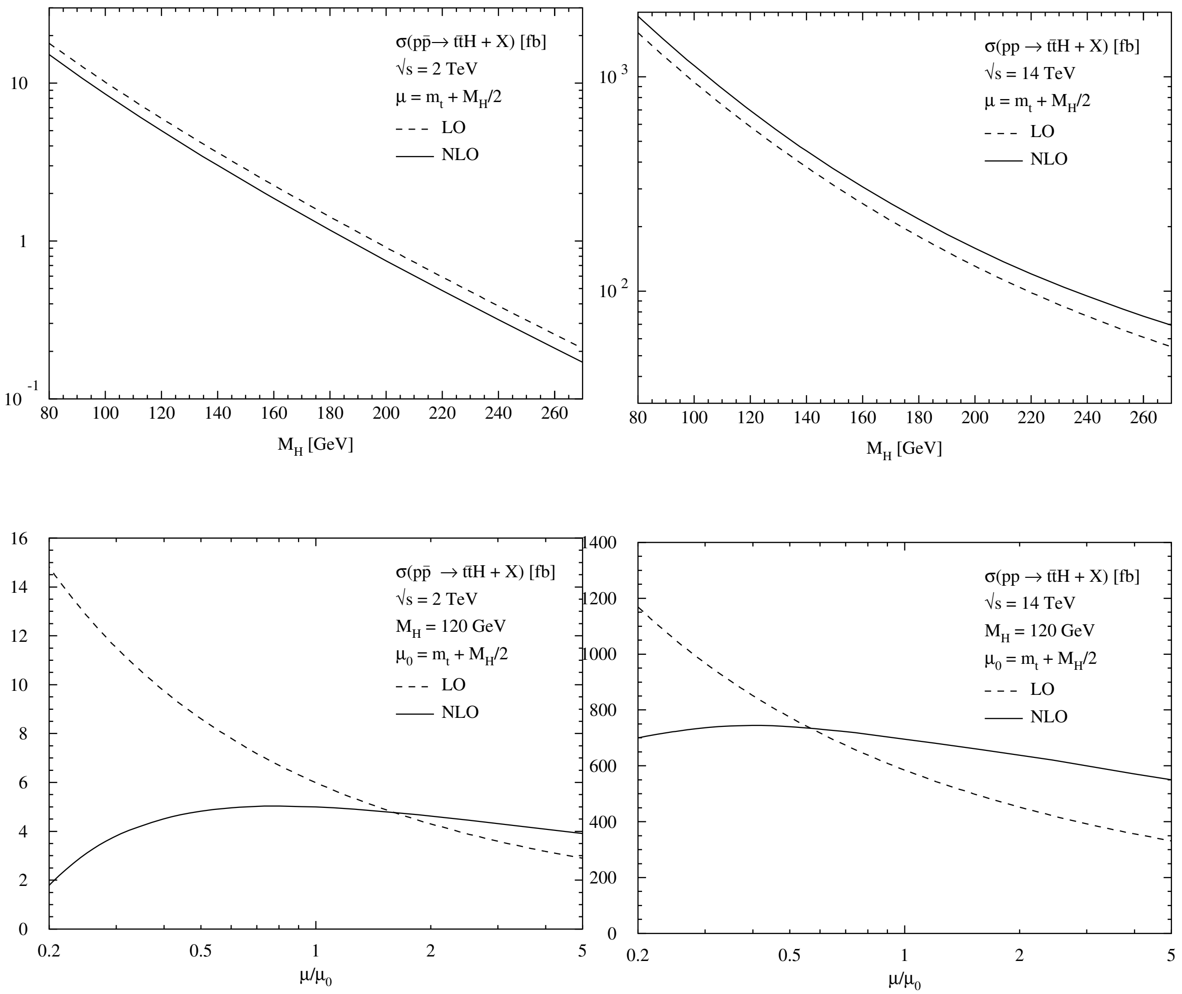
W. Beenakker et al., *Phys. Rev. Lett.* 87 (2001) 201805

They have been calculated independently with good agreement for the $q\bar{q}$ channel

S. Dawson and L. Reina, *Phys. Rev. Lett.* 87 (2001) 201804

S. Dawson, L. Reina and D. Wackeroth, Phys. Rev. D 65 (2002) 053017






The NLO corrections give a prediction sensibly more stable than the LO one with respect to variations of the renormalisation and factorisation scales

The $K$-factors defined by $\sigma_{NLO}/\sigma_{LO}$ amount to about 0.8 for Tevatron energies and 1.2 for LHC energies

# Main search channels at LHC

$m_H < 2M_Z$

$H \to \gamma\gamma, \qquad WH, \qquad t\bar{t}H\ (H \to \gamma\gamma)$

$t\bar{t}H\ (H \to b\bar{b})$

$t\bar{t}H\ (H \to WW^{(*)})$

F. Maltoni, D. Rainwater and S. Willenbrock, hep-ph/0202205

$t\bar{t}H\ (H \to \tau^+\tau^-)$

A. Belyaev and L. Reina, hep-ph/0205270

$H \to ZZ^* \to 4l, \qquad H \to WW^* \to l\nu l\nu$

$m_H > 2M_Z$

$H \to ZZ \to 4l$

$qqH \to ZZ \to ll\nu\nu+$ fwd jets

$qqH \to ZZ \to lljj+$ fwd jets

$qqH \to WW \to l\nu jj+$ fwd jets

# Backgrounds evaluation

## Two complementary approaches

- LO calculations for multiparton final states, based on exact matrix elements of the hard subprocesses incorporated in MC event generators suitably interfaced to the shower evolution producing the real final state hadrons, *e.g.* CompHEP, GRACE, MADGRAPH, ACERMC*, ALPGEN**

  * B.P. Kersevan and E. Richter-Was, hep-ph/0201302

  ** M.L. Mangano et al., hep-ph/0206293

- NLO QCD calculations for specific final states (with restricted number of final state particles, due to the complexity of the calculations)

# Available NLO background calculations

- QCD $\gamma\gamma$ background known at NLO, including all relevant fragmentation effects. They are included in the program DIPHOX

  T. Binoth et al., Eur. Phys. J. C16 (2000) 311, and hep-ph/0203064

- recent calculation of $gg \to \gamma\gamma$ at two loop level

  Z. Bern, L. Dixon and C. Schmidt, hep-ph/0206194

- $pp(\bar{p}) \to Wb\bar{b},\ Zb\bar{b}$

  R.K. Ellis and S. Veseli, Phys. Rev. D60 (1999) 011501

  J. Campbell, hep-ph/0105226

- $pp(\bar{p}) \to Wjj,\ Zjj$

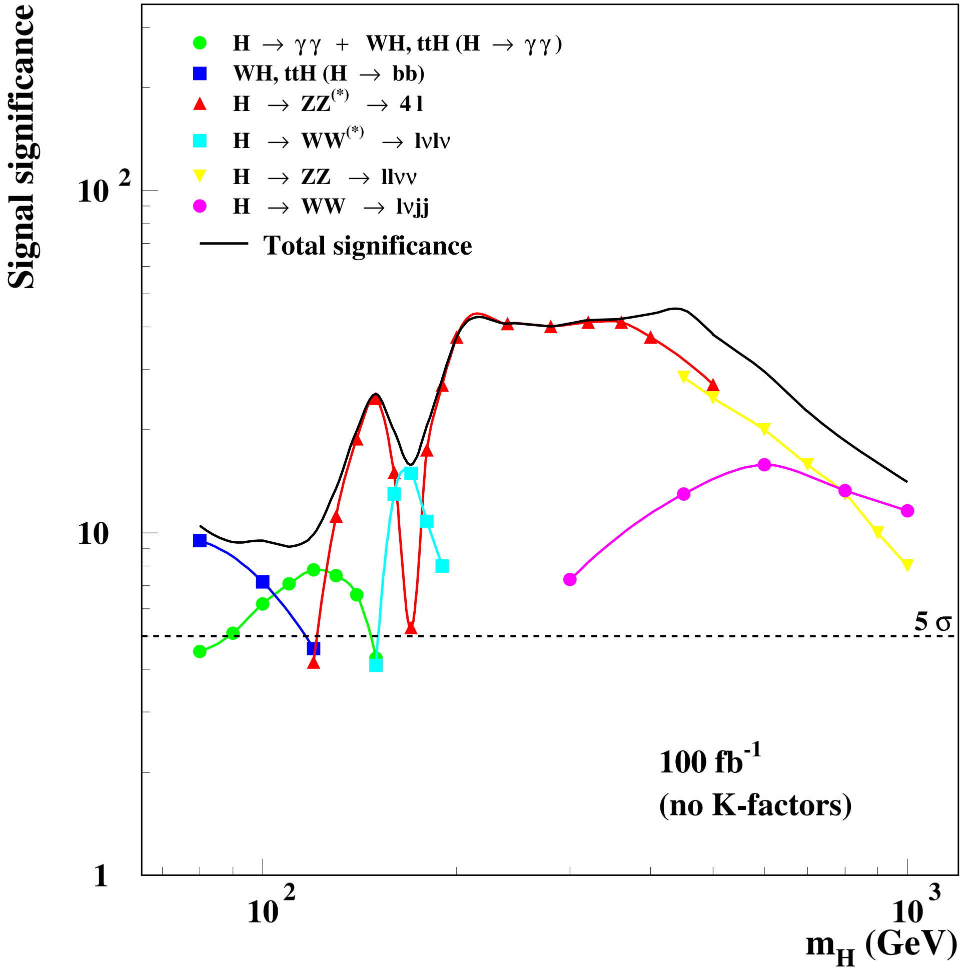
  J. Campbell and R.K. Ellis, hep-ph/0202176

- $pp(\bar{p}) \to VV$ recently interfaced to LL Parton Shower

  S. Frixione and B.R. Webber, hep-ph/0204244

- QCD $H + jj$ production via gluon fusion

  V. Del Duca et al., Nucl. Phys. B616 (2001) 367



Signal significance
$H \to \gamma\gamma$ + WH, ttH ($H \to \gamma\gamma$)
WH, ttH ($H \to bb$)
$H \to ZZ^{(*)} \to 4l$
$H \to WW^{(*)} \to l\nu l\nu$
$H \to ZZ \to ll\nu\nu$
$H \to WW \to l\nu jj$
Total significance
$5\sigma$
100 $fb^{-1}$
(no K-factors)
$10^2$
10
1
$10^2$
$10^3$
$m_H$ (GeV)

Up to now the main production and decays channels have also been studied within ATLAS and CMS with full detector simulation taken into account

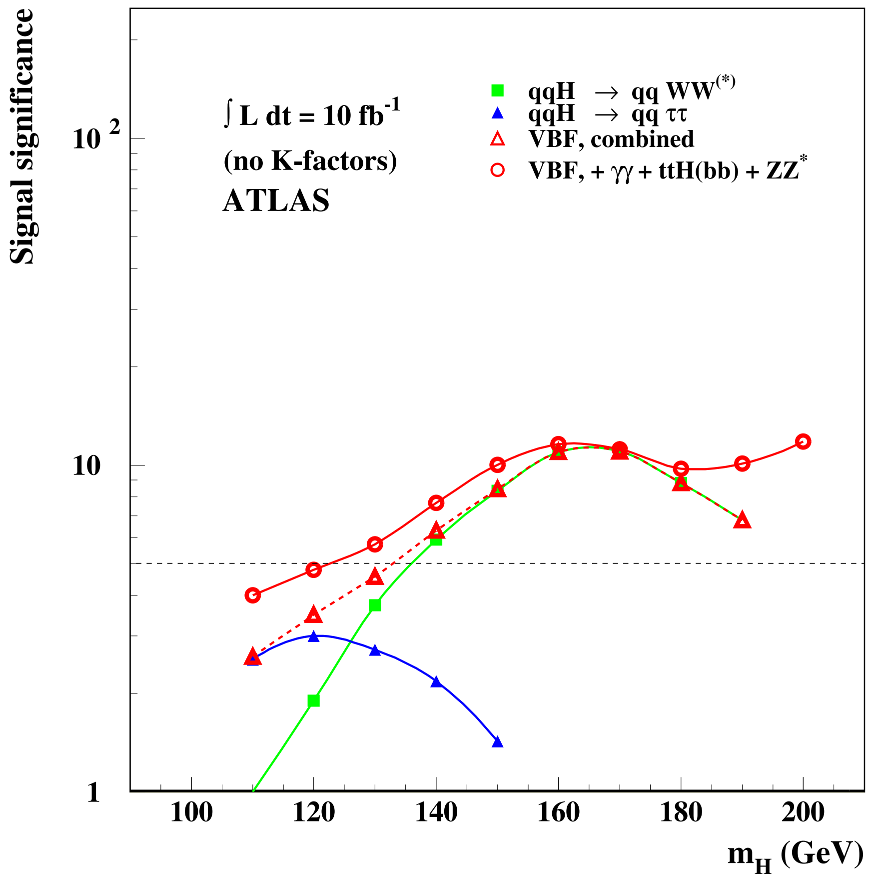
CMS Note 2001/054, hep-ph/0111312

CMS Note 2002/006, hep-ph/0201249

Ongoing activities in the study of VBF channels, which are important to increase the potential for Higgs discovery at low mass (and also for the measurement of Higgs parameters, see later).

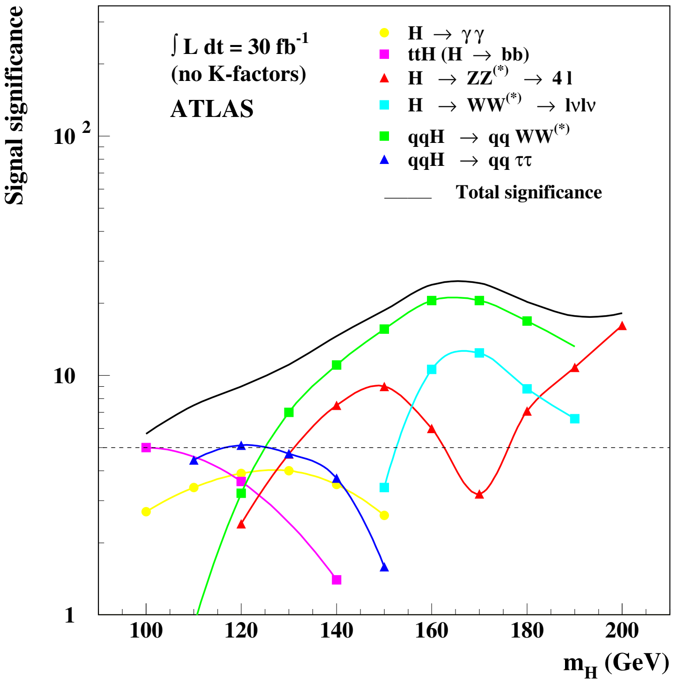
Crucial to this aim on the experimental side

- fwd jet tagging
- jets from pile-up in the central/forward region




K. Jakobs, ATLAS week, Clermont-Ferrand, June 2002

VBF channels are discovery channels at low luminosity



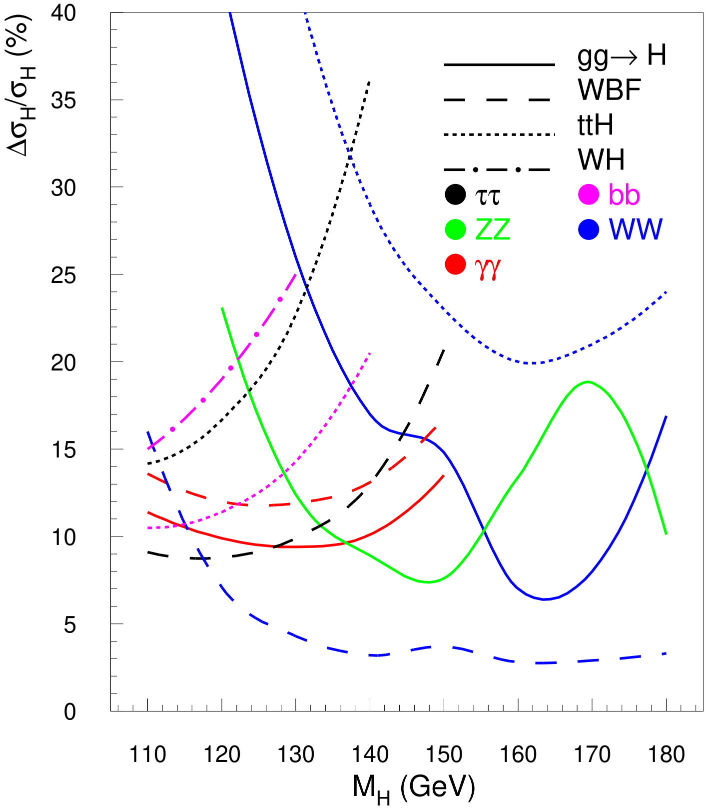

K. Jakobs, ATLAS week, Clermont-Ferrand, June 2002

VBF channels improve the sensitivity significantly in the low mass region

A study by CMS for low and high mass (300–600 GeV) Higgs in

CMS Note 2002/016

CMS Note 2001/050




Relative accuracies on the measurement of the cross section of a scalar SM-like Higgs boson. All channels have been rescaled to a total integrated luminosity of 200 fb$^{-1}$ (100 fb$^{-1}$ per detector), except $pp \to t\bar{t}H$, $H \to WW$ and $q\bar{q} \to WH$, $H \to b\bar{b}$ for which we use 300 fb$^{-1}$ , and $gg \to H$, $H \to WW$ that was studied for 30 fb$^{-1}$

A. Belyaev and L. Reina, hep-ph/0205270

# Higgs couplings to fermions and gauge bosons

The LHC will allow not only to discover the Higgs but also to study its properties

In principle the measurement of the Higgs couplings to fermions can be performed by using the relation of the couplings with the partial width

$$\Gamma_f = \Gamma(H \to f\bar{f}) = c_f \frac{g^2_{Hff}}{8\pi} \left(1 - \frac{4m_f^2}{m_H^2}\right)^{\frac{3}{2}} m_H$$

related to the experimentally measured rate by

$$R(H \to f\bar{f}) = \int Ldt \cdot \sigma(pp \to H) \cdot \frac{\Gamma_f}{\Gamma}$$

With this approach $\sigma(pp \to H)$ and $\Gamma$ need to be known from theory

A model independent analysis can only be made by considering ratios of couplings through the measurement of ratios of rates in two different final states, and this can be done by exploiting different production and decay mechanisms available at LHC

In the ratios the QCD uncertainties and other initial state uncertainties like luminosity and PDF errors cancel

With the assumption that $\Gamma_z/\Gamma_w = z_{SM}$, each channel provides a measurement of the ratio $Z_j^{(i)}$ defined as

$$Z_j^{(i)} = \frac{\Gamma_i \Gamma_j}{\Gamma}$$

The mass range of an intermediate mass scalar Higgs boson is naturally divided into two main regions, $M_H \leq 140$ GeV and $140 < M_H \leq 180$ GeV

For $M_H \leq 140$ GeV, the following channels are relevant

$$gg \to H \ \text{ with } \ H \to \gamma\gamma$$
$$qq \to qqH \ \text{ with } \ H \to \gamma\gamma,\ \tau\tau,\ WW$$
$$q\bar{q}, gg \to t\bar{t}H \ \text{ with } \ H \to b\bar{b}, \tau\tau$$

while for $140 < M_H \leq 180$ GeV

$$gg \to H \ \text{ with } \ H \to ZZ,\ WW$$
$$qq \to qqH \ \text{ with } \ H \to WW$$

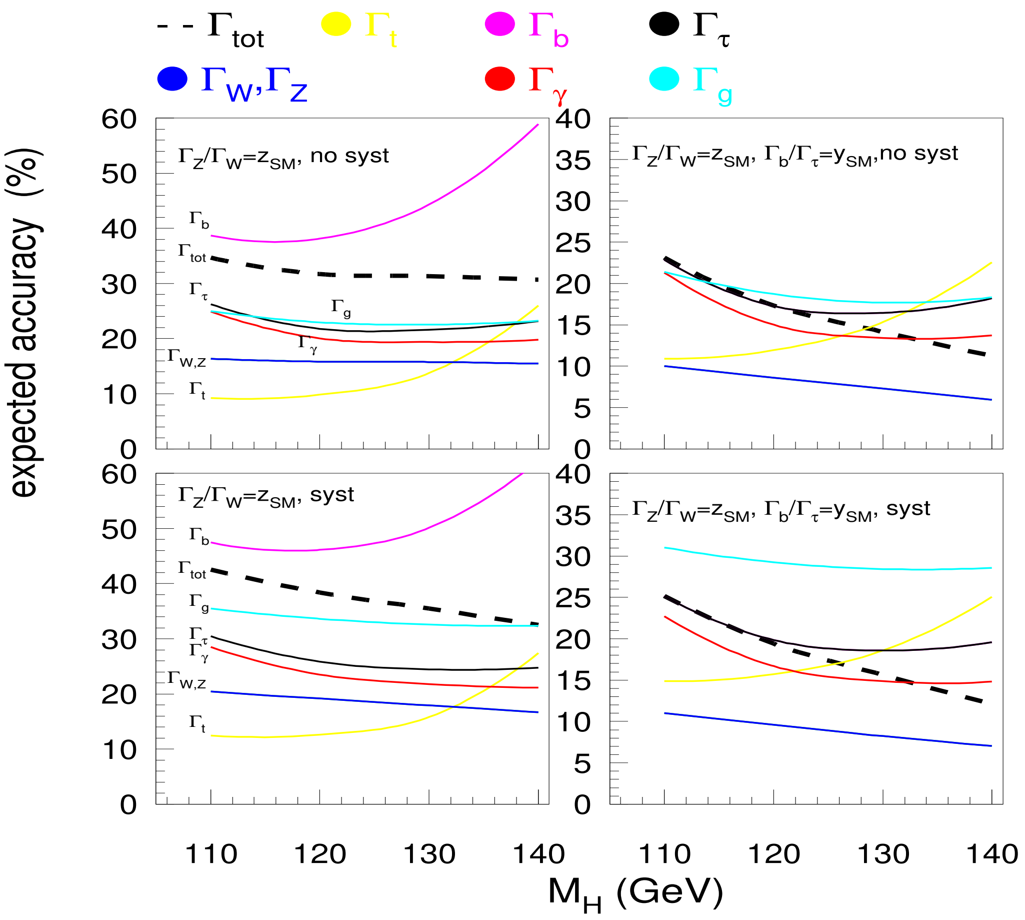
For $M_H > 140$ GeV there is no channel that can provide a handle on $\Gamma_b$

$$
\begin{aligned}
\Gamma_t &= \frac{Z_\tau^{(t)}\sqrt{Z_w^{(w)}}}{Z_\tau^{(w)}}\sqrt{\Gamma} \\
\Gamma_b &= \frac{Z_b^{(t)}Z_\tau^{(w)}}{Z_\tau^{(t)}\sqrt{Z_w^{(w)}}}\sqrt{\Gamma} \\
\Gamma_\tau &= \frac{Z_\tau^{(w)}}{\sqrt{Z_w^{(w)}}}\sqrt{\Gamma} \\
\Gamma_w &= \sqrt{Z_w^{(w)}}\sqrt{\Gamma} \\
\Gamma_\gamma &= \frac{Z_\gamma^{(w)}}{\sqrt{Z_w^{(w)}}}\sqrt{\Gamma} \\
\Gamma_g &= \frac{Z_\gamma^{(g)}\sqrt{Z_w^{(w)}}}{Z_\gamma^{(w)}}\sqrt{\Gamma}
\end{aligned}
$$

$\Gamma$ follows from the assumption

$$\Gamma = \Gamma_b + \Gamma_\tau + \Gamma_w + \Gamma_z + \Gamma_g + \Gamma_\gamma$$

$$\sqrt{\Gamma} = \frac{1}{\sqrt{Z_w^{(w)}}}\left[Z_\tau^{(w)}\left(1+\frac{Z_b^{(t)}}{Z_\tau^{(t)}}\right) + Z_w^{(w)}\left(1+z_{SM}\right) + \frac{Z_w^{(w)}Z_\gamma^{(g)}}{Z_\gamma^{(w)}} + Z_\gamma^{(w)}\right]$$




A. Belyaev and L. Reina, hep-ph/0205270

A total integrated luminosity of 200 $\mathrm{fb}^{-1}$ (100 $\mathrm{fb}^{-1}$ per detector) is assumed

syst means systematic theoretical error of 20% for $gg \to H$, of 5% for $qq \to qqH$, and of 10% for $pp \to t\bar{t}H$

Inclusion of the channel $pp \to t\bar{t}H,\ H \to \tau^+\tau^-$ essential to

- determine in a model independent way ratios of couplings like

$$\frac{\Gamma_b}{\Gamma_\tau} = \frac{Z_b^{(t)}}{Z_\tau^{(t)}} \quad \text{and} \quad \frac{\Gamma_t}{\Gamma_g} = \frac{Z_\tau^{(t)} Z_\gamma^{(w)}}{Z_\tau^{(w)} Z_\gamma^{(g)}}$$

  with accuracies of the order of 20-30%

- test the $\Gamma_z/\Gamma_w = z_{SM}$ universality assumption even for $M_H < 140$ GeV by comparing the two ratios

$$\frac{Z_b^{(wH)}}{Z_b^{(t)}} \quad \text{and} \quad \frac{Z_\tau^{(w)}}{Z_\tau^{(t)}}$$

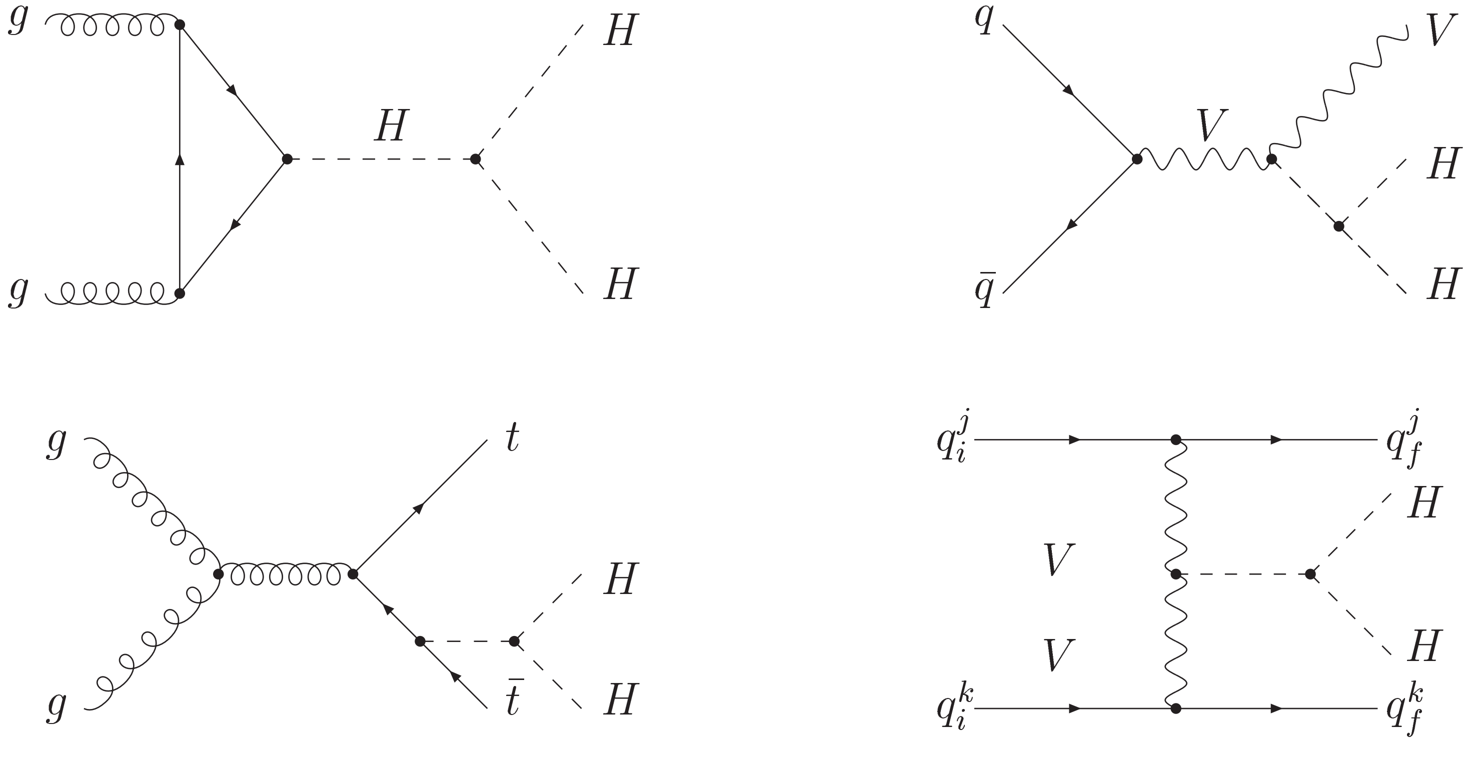
  both ratios can be measured at the 20-30% level depending on the value of $M_H$

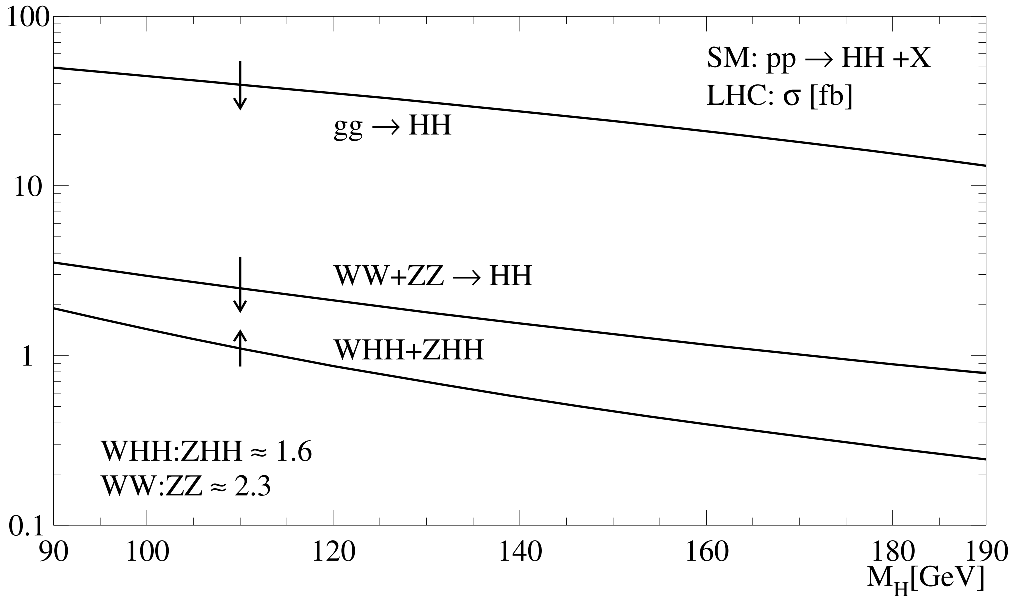
# Higgs self-coupling

The SM predicts also the existence of trilinear and quartic interactions, with couplings given by

$$\lambda_{HHH} = 3\frac{m_h^2}{v}\,, \quad \lambda_{HHHH} = 3\frac{m_h^2}{v^2}$$

The coupling $\lambda_{hhh}$ can only be investigated in processes with two intermediate Higgs bosons






A. Djouadi et al., Eur. Phys. J. C **10** (1999) 45

Given the low production rates and the potentially large backgrounds associated to the final states with the best signal rates, detection of SM Higgs pairs with standard luminosity at LHC ($10^{34}$ cm$^{-2}$ $s^{-1}$) is difficult. It has been studied the possibility of an high luminosity option of the machine ($10^{35}$ cm$^{-2}$ $s^{-1}$)

F. Gianotti, M.L. Mangano, T.Virdee et al., SLHC Workshop, CERN, hep-ph/0204087

Among the considered channels, $gg \rightarrow HH$ looks promising

The $gg \to HH$ channel is useful for $m_h \geq 170$ GeV, because otherwise the final state is $b\bar{b}b\bar{b}$ which is overwhelmed by QCD background

The following particular signature has been considered:

$$gg \to W^+W^-W^+W^- \to l^\pm \nu jj l^\pm \nu jj$$

this channel has also been considered by U. Baur, T. Plehn and D. Rainwater, hep-ph/0206024

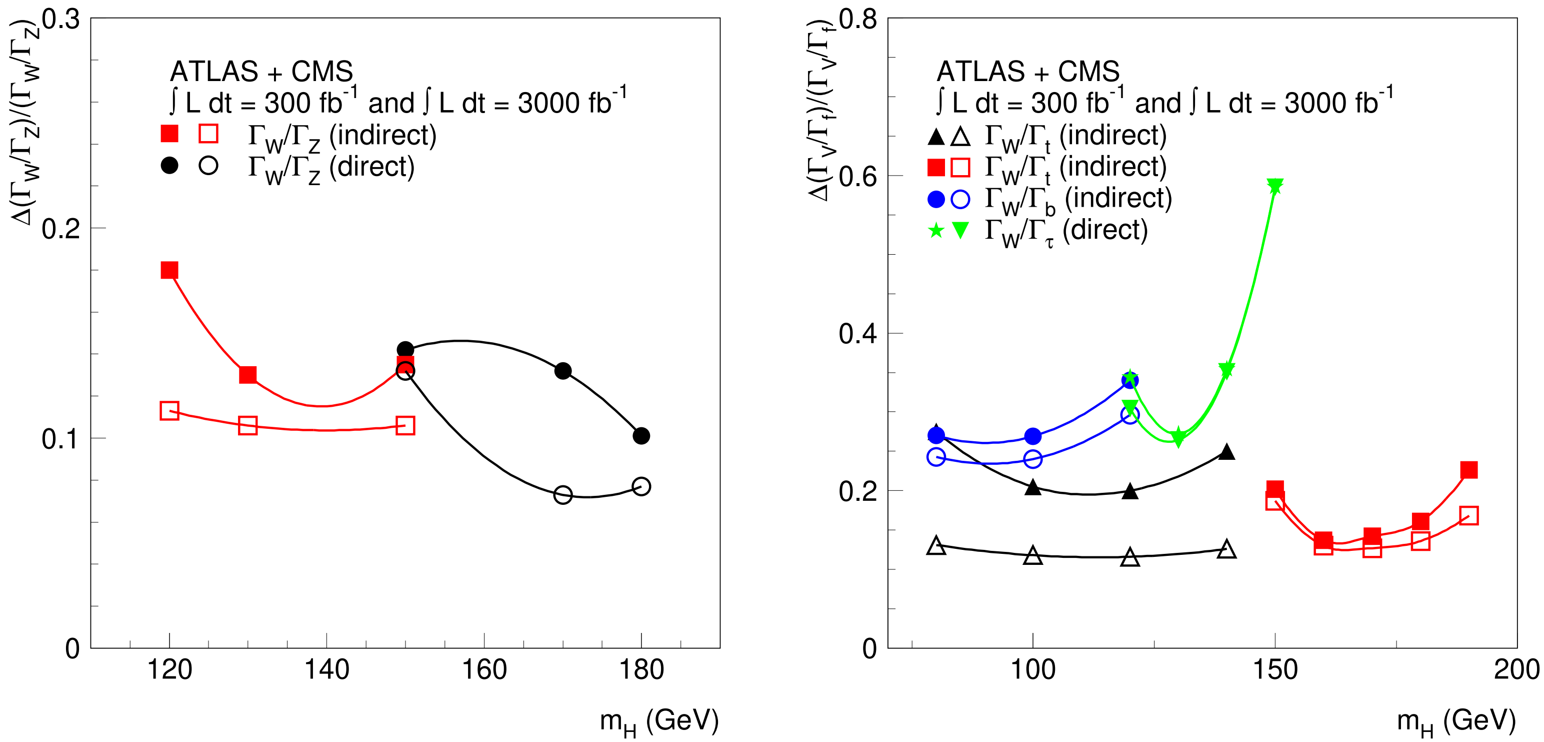
## Potential backgrounds

1. $t\bar{t} + jets$, where the second lepton arises from b decays
2. $WZ + jets$, where one of the Z leptons is not identified
3. $t\bar{t}W$
4. $WWWjj$, including $W(h \to WW)jj$
5. $t\bar{t}t\bar{t}$

| $m_h$ | Signal | $t\bar{t}$ | $W^\pm Z$ | $W^\pm W^+ W^-$ | $t\bar{t}W^\pm$ | $t\bar{t}t\bar{t}$ | $S/\sqrt{B}$ |
|---|---|---|---|---|---|---|---|
| 170 GeV | 350 | 90 | 60 | 2400 | 1600 | 30 | 5.4 |
| 200 GeV | 220 | 90 | 60 | 1500 | 1600 | 30 | 3.8 |

This allows a measurement of $\lambda_{HHH}$ with statistical errors at the 20% level

# Improvements at SLHC on coupling ratios




F. Gianotti, M.L. Mangano, T.Virdee et al., SLHC Workshop, CERN, hep-ph/0204087

In most cases the ratios of couplings could be measured with precisions of 10% or better, which represents in some cases an improvement of a factor of two on the precision expected at the standard LHC

# Conclusions

- All Higgs production channels are theoretically known at NLO order (NNLO for the gluon fusion process), which implies a theoretical uncertainty not larger than 20%
- Some important backgrounds are known at NLO
- Several codes based on LO multiparticle matrix elements interfaced to parton shower MC are available for simulations
- Recently a lot of work has been done to study signal and backgrounds including full detector simulations
- VBF channels increase the discovery potential especially in the low mass region
- LHC will allow a model independent analysis of Higgs couplings to vector bosons and fermions at the 10–25% level for low Higgs mass. For $m_H > 140$ GeV the study of couplings to fermions becomes difficult
- Higgs self-coupling can be quantitatively studied only with an upgraded luminosity option of the machine (($10^{35}$ cm$^{-2}$ $s^{-1}$)) for Higgs masses in the range 150–200 GeV