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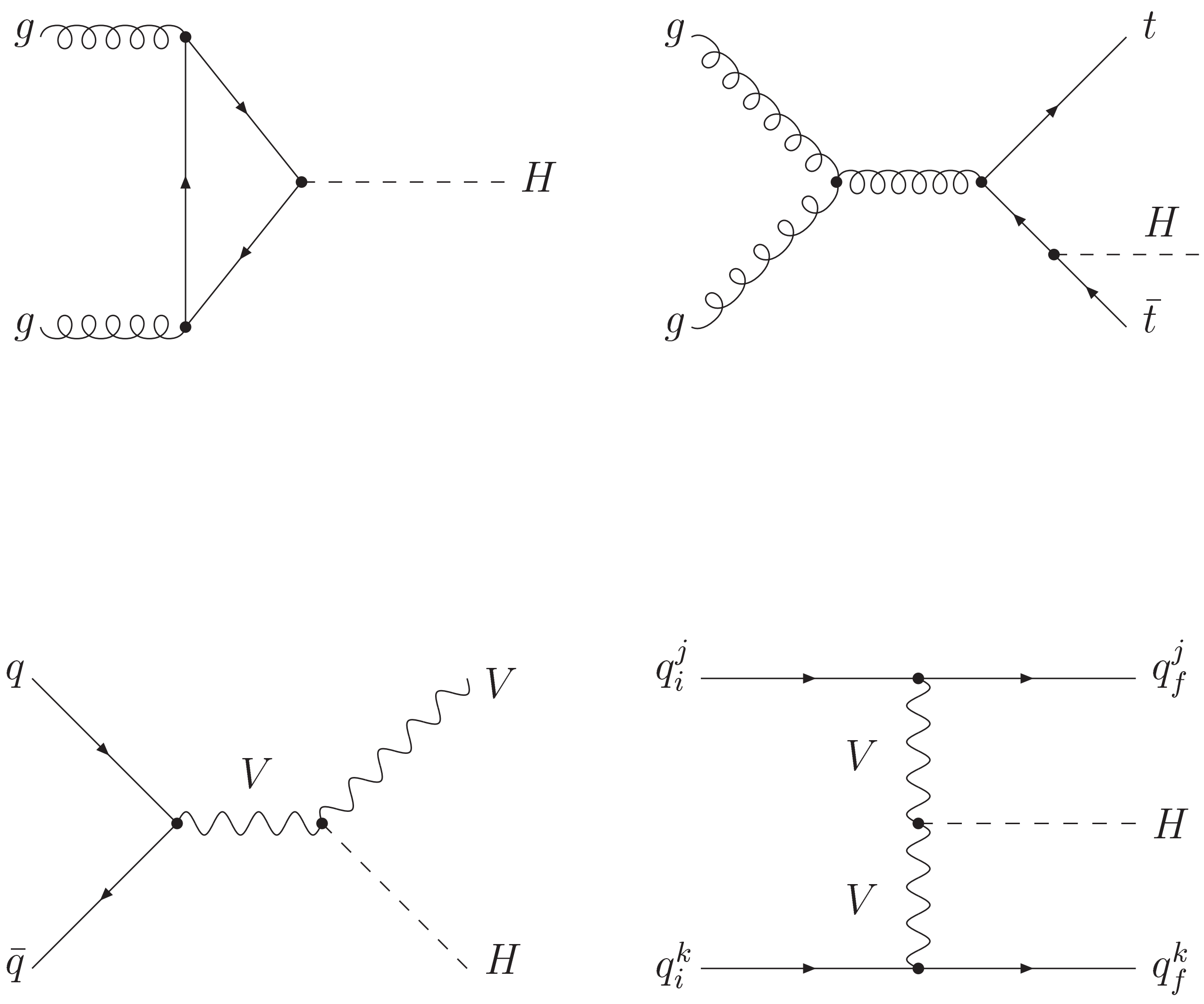
Prospects of Higgs properties determination at LHC

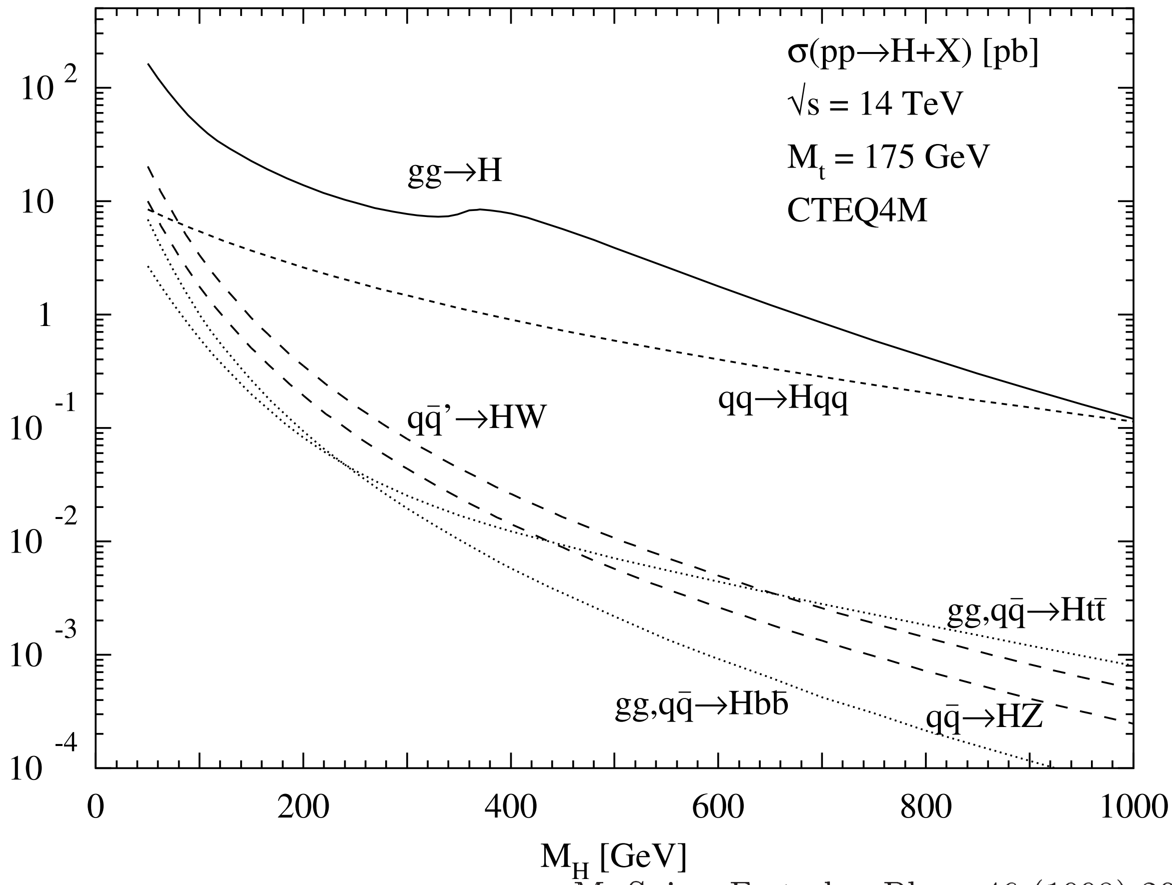
Contents

RADCOR–LOOPS and LEGS 2002, Kloster Banz, 11 September, 2002

SM Higgs production at LHC



Signal cross 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)

see talks by J. Smith, R. Harlander, S. Dittmaier

Main search channels at LHC

$m_H < 2M_Z$ $\quad H \to \gamma\gamma, \quad WH, \quad t\bar{t}H\ (H \to \gamma\gamma)$

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

V. Drollinger, T. Müller and D. Denegri, hep-ph/0201249

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

V. Drollinger, T. Müller and D. Denegri, hep-ph/0111312

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

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

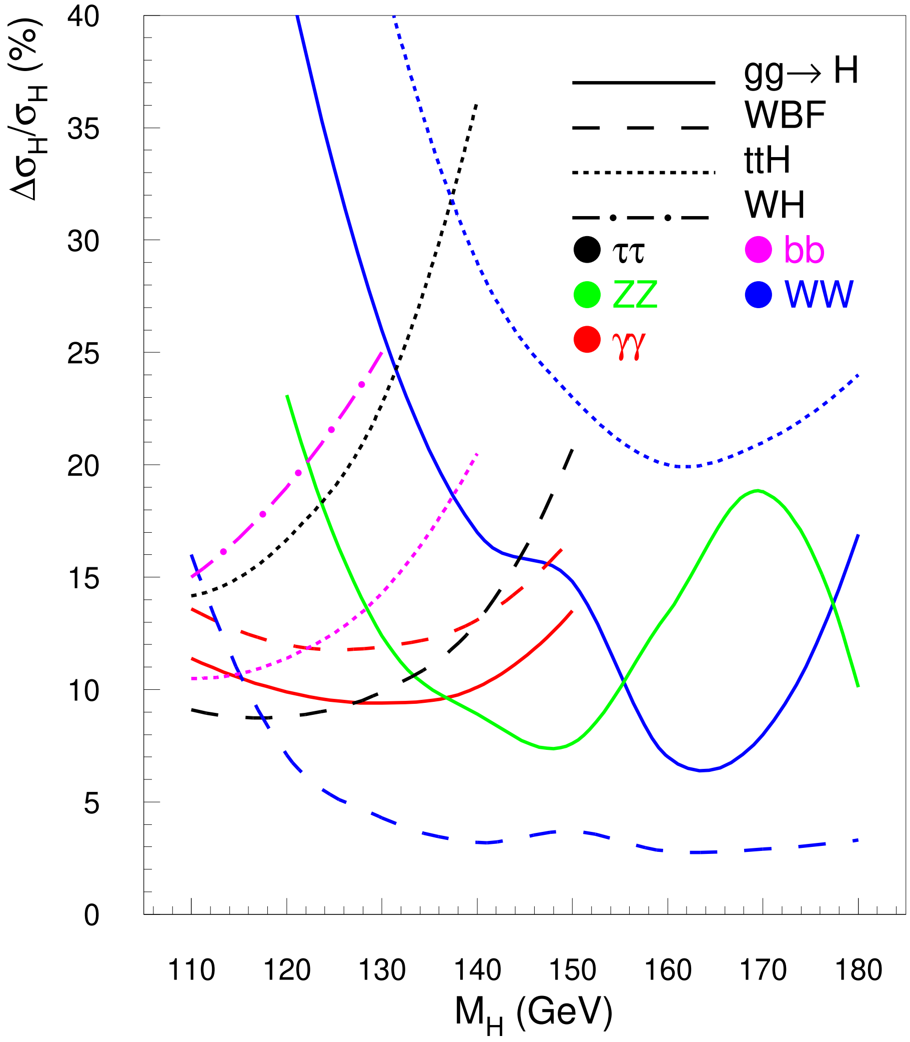
$H \to ZZ^* \to 4l, \quad H \to WW^* \to l\nu l\nu$

$m_H > 2M_Z$ $\quad H \to ZZ \to 4l, \quad H \to WW \to l\nu l\nu$

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

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

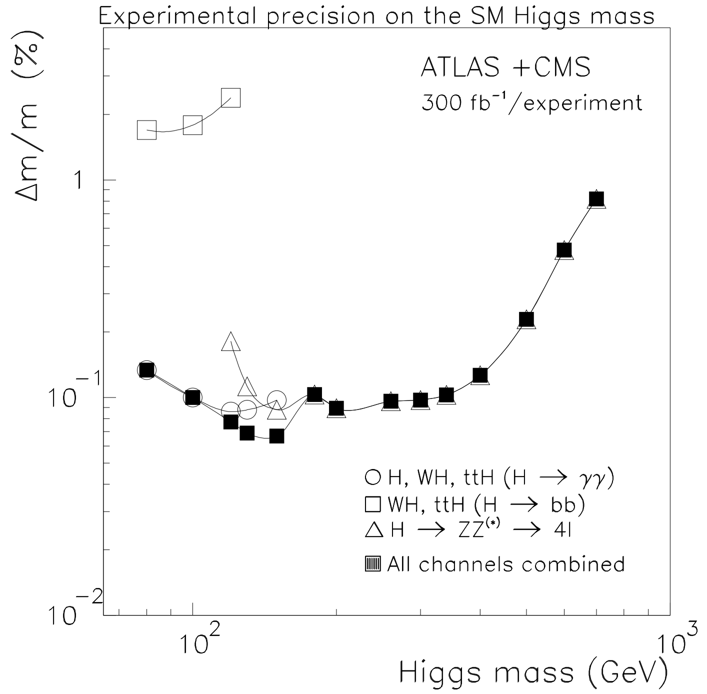
$qqH \to WW \to l\nu jj +$ fwd jets

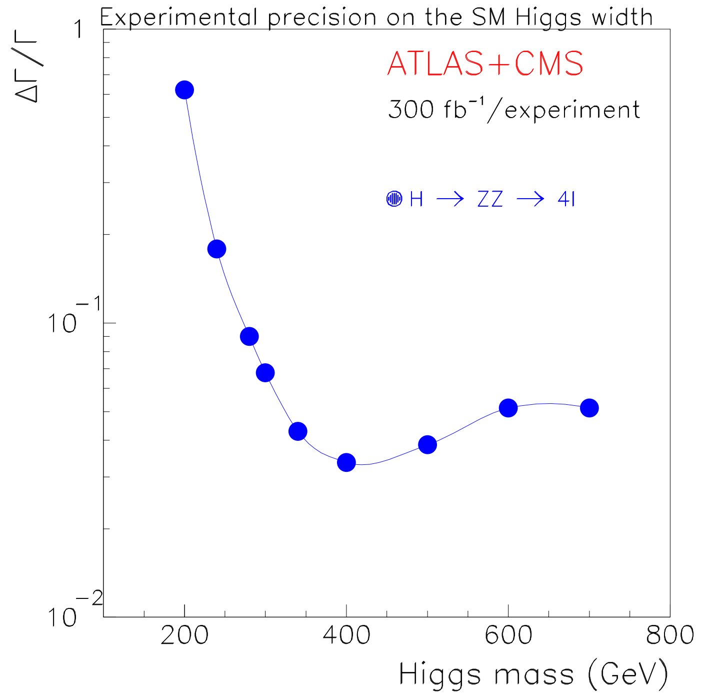


A. Belyaev and L. Reina, hep-ph/0205270

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 $q\bar{q} \to WH$, $H \to b\bar{b}$ which correspond to 300 fb^{-1}, and $gg \to H$, $H \to WW$ that was studied for 30 fb^{-1}

Direct determination of Higgs mass and width





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

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

With this approach $\sigma(pp \to H)$ and Γ 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

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

$$X_\gamma = \frac{\Gamma_W \Gamma_\gamma}{\Gamma} \qquad \text{from} \qquad qq \to qqH,\ H \to \gamma\gamma$$

$$X_\tau = \frac{\Gamma_W \Gamma_\tau}{\Gamma} \qquad \text{from} \qquad qq \to qqH,\ H \to \tau\tau$$

$$X_W = \frac{\Gamma_W^2}{\Gamma} \qquad \text{from} \qquad qq \to qqH,\ H \to WW^*$$

$$Y_\gamma = \frac{\Gamma_g \Gamma_\gamma}{\Gamma} \qquad \text{from} \qquad gg \to H \to \gamma\gamma$$

$$Y_Z = \frac{\Gamma_g \Gamma_Z}{\Gamma} \qquad \text{from} \qquad gg \to H \to ZZ^*$$

$$Y_W = \frac{\Gamma_g \Gamma_W}{\Gamma} \qquad \text{from} \qquad gg \to H \to WW^*$$

$$T_b = \frac{\Gamma_t \Gamma_b}{\Gamma} \qquad \text{from} \qquad gg \to t\bar{t}H,\ H \to b\bar{b}$$

$$T_W = \frac{\Gamma_t \Gamma_W}{\Gamma} \qquad \text{from} \qquad gg \to t\bar{t}H,\ H \to WW^*$$

$$U_b = \frac{\Gamma_W \Gamma_b}{\Gamma} \qquad \text{from} \qquad q\bar{q} \to WH,\ H \to b\bar{b}$$

D. Zeppenfeld hep-ph/0203123

D. Zeppenfeld et al., Phys. Rev. D62, hep-ph/0002036

The analysis has been updated with the inclusion of the channel $pp \to t\bar{t}H,\ H \to \tau\tau$

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

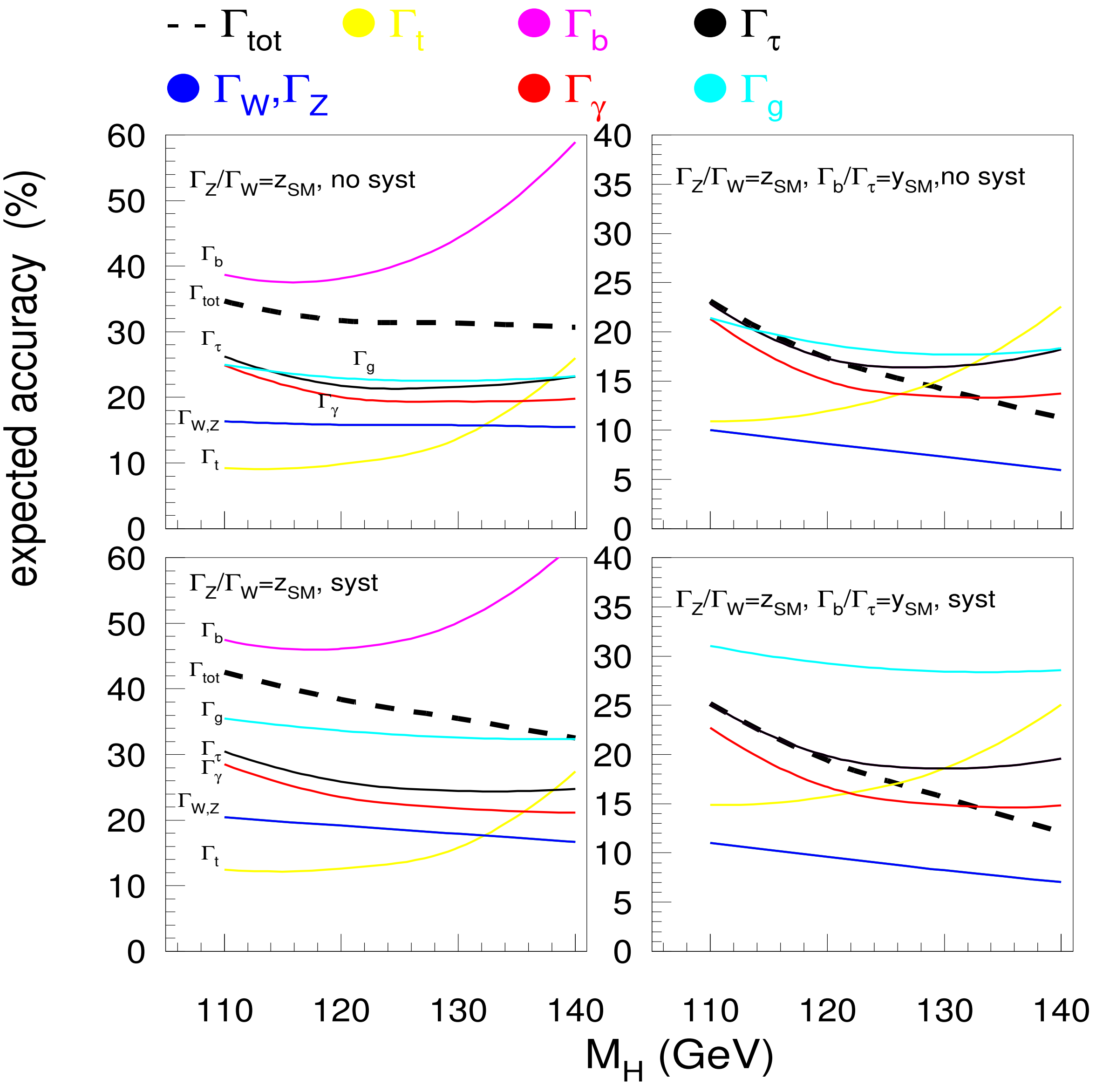
$$
\begin{aligned}
\Gamma_t &= \frac{Z_\tau^{(t)}\sqrt{Z_w^{(w)}}}{Z_\tau^{(w)}}\sqrt{\Gamma} \\
\Gamma_b &= \frac{Z_b^{(t)}Z_\tau^{(w)}}{Z_\tau^{(t)}\sqrt{Z_w^{(w)}}}\sqrt{\Gamma} \\
\Gamma_\tau &= \frac{Z_\tau^{(w)}}{\sqrt{Z_w^{(w)}}}\sqrt{\Gamma} \\
\Gamma_w &= \sqrt{Z_w^{(w)}}\sqrt{\Gamma} \\
\Gamma_\gamma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

Γ follows from the assumption

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

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

Indirect determination of the total Higgs width



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

A total integrated luminosity of 200 fb^{-1} (100 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

$H \to b\bar{b}$ in Weak Boson Fusion

in collaboration with

M.L. Mangano, M. Moretti, R. Pittau and A.D. Polosa

Up to now the $H \to b\bar{b}$ coupling has been studied in the channels of associate production $Ht\bar{t}$ and HW

Can we add information by exploiting the WBF production mechanism?

Signal rate proportional to $y_{Hbb} \cdot y_{HVV}$

Typical signature: central $b\bar{b}$ pair + pair of jets in the fwd and bckwd rapidity region

Main backgrounds:

- QCD $b\bar{b}jj$ production
- QCD four jets production (with two light jets mistagged as b jets)
- QCD $Z(\to b\bar{b})jj$
- QCD $W/Z(\to jj)b\bar{b}$
- QCD $t\bar{t} \to b\bar{b}+$ jets
- QCD multiple overlapping events (especially at high luminosity)

Parton level study performed by means of the event generator **ALPGEN**

M.L. Mangano, M. Moretti, F. P., R. Pittau and A.D. Polosa, hep-ph/0206293

Event selection

$$\begin{aligned} p_T^b &> 30 \text{ GeV} \\ |\eta_b| &< 2.5 \\ \Delta R_{bb} &> 0.7 \\ |m_{bb} - m_H| &< \delta_m \cdot m_H \\ \epsilon_b &= 0.5 \end{aligned}$$

$$\begin{aligned} p_T^j &> 60 \text{ GeV} \\ |\eta_{j_1} - \eta_{j_2}| &> 4.2 \\ \Delta R_{jj}, \Delta R_{jb} &> 0.7 \\ m_{jj} &> 1000 \text{ GeV} \\ 0.01 < \epsilon_{\text{mis}} &< 0.05 \end{aligned}$$

- selection a)

$$2.5 < |\eta_j| < 5, \quad \eta_{j_1}\eta_{j_2} < 0, \quad \Delta R_{bb} < 2$$

- selection b)

$$|\eta_j| < 5$$

The cut $|\eta_{j_1} - \eta_{j_2}| > 4.2$ allows to suppress the "background" due to H + 2 jets QCD production

V. Del Duca et al., Phys. Rev. Lett. 87, 122001 (2001)

Results

Table 1: Configuration (a). Upper values correspond to $Q^2 = m_H^2$ while lower values correspond to $\langle {p_T}^2 \rangle$. The $jjjj$ entry does not include the squared $b-$mistagging efficiency. The integrated luminosity is 600 fb^{-1}.

m_H	115 GeV	120 GeV	140 GeV
Signal	4385	4160	1657
$b\bar{b}jj$	7.2×10^5	6.4×10^5	4.6×10^5
	8.6×10^5	8.0×10^5	5.7×10^5
$jjjj$	5.9×10^7	5.1×10^7	3.6×10^7
	6.4×10^7	6.1×10^7	4.1×10^7
$(Z \to b\bar{b})jj$	5.5×10^2	3.8×10^2	1.0×10^2
$Zjj_{\mathrm{smear.}}$	1.3×10^3	6.8×10^2	1.1×10^1

Table 2: Same as Table 1, for configuration (b). The integrated luminosity is 600 fb^{-1}.

m_H	115 GeV	120 GeV	140 GeV
Signal	19290	18610	9090
$b\bar{b}jj$	4.9×10^6	4.9×10^6	3.6×10^6
	6.0×10^6	5.3×10^6	4.7×10^6
$jjjj$	8.3×10^8	8.3×10^8	7.2×10^8
	9.5×10^8	9.5×10^8	9.5×10^8
$(Z \to b\bar{b})jj$	4.5×10^3	2.8×10^3	1.1×10^3
$Zjj_{\mathrm{smear.}}$	1.6×10^4	8.3×10^3	7.7×10^2

Overlapping events due to multiple pp collisions

four possible combination of double scattering events leading to $b\bar{b}jj$:

- $pp \to jj \oplus b\bar{b}$
- $pp \to jj \oplus j_b j_b$
- $pp \to jj_b \oplus jj_b$
- $pp \to b\bar{b} \oplus b\bar{b}$

The cross sections scale linearly with the luminosity $\to$ they represent a potential threat at high luminosity

At 600 fb^{-1} we find

process	n. of evts a)	n. of evts b)
$pp \to jj \oplus b\bar{b}$	113400	402000
$pp \to jj \oplus j_b j_b$	8600	30600
$pp \to jj_b \oplus jj_b$	100	10800

$pp \to b\bar{b} \oplus b\bar{b}$ give a negligible contribution

Table 3: The sensitivity, for two different values of the factorization/renormalization scale Q^2. The mistagging efficiency of light jets, ϵ_{mis}, is $\epsilon_{\text{mis}} = 0.01$. The integrated luminosity is 600 fb^{-1}.

m_H	115 GeV	120 GeV	140 GeV
(a) $S/\sqrt{B}$	4.8	4.7	2.2
	4.4	4.3	2.0
(b) $S/\sqrt{B}$	8.3	8.0	4.5
	7.5	7.7	4.0

Table 4: The same as Table 3 but with a mistagging efficiency of $\epsilon_{\text{mis}} = 0.05$.

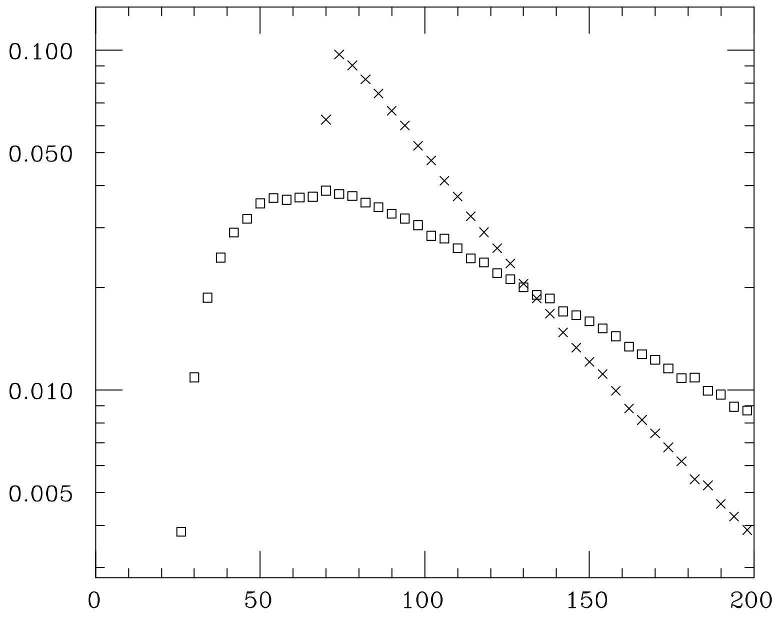
m_H	115 GeV	120 GeV	140 GeV
(a) $S/\sqrt{B}$	3.9	3.9	1.7
	3.7	3.6	1.6
(b) $S/\sqrt{B}$	6.6	6.4	3.5
	6.5	6.2	3.1

Even if $S/\sqrt{B}$ at the level of 5σ, the ratio S/B is only of the order of 0.5%[a]

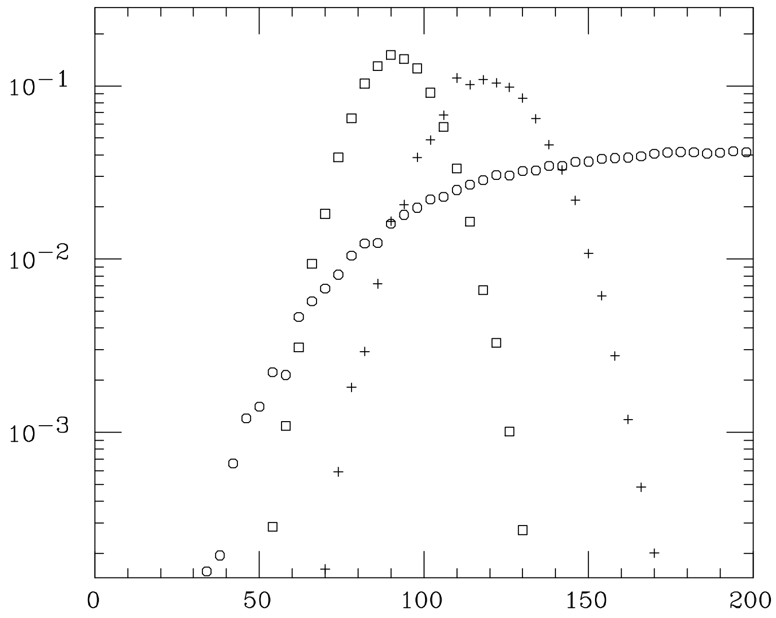
$\rightarrow$ the background need to be known with accuracy at the 0.1% level. Therefore it should be determined entirely from the data

It is important to see the $b\bar{b}$ invariant mass distributions

[a] A increase in S/B can be obtained by exploting rapidity gaps, as suggested in V.A. Khoze et al., hep-ph/0207365. But this would require a full detector simulation.



The shape of m_{bb} (GeV) for the most sizeable backgrounds: QCD $b\bar{b}jj$ (squares) and multiple scattering events (crosses)



The shape of m_{bb} (GeV) assuming a gaussian smearing of 12% in the signal (crosses), the Zjj background (squares) and the $t\bar{t}$ reducible background (circles)

Table 5: The statistical significance in b-quark Yukawa coupling in the configurations (a) and (b), $\delta y/y = \sqrt{B}/2S$, assuming the knowledge of the HWW coupling. Upper entries refer to the low luminosity case 60 fb^{-1} while lower ones refer to 600 fb^{-1}. Here $\epsilon_{\rm mis} = 0.01$.

m_H	115 GeV	120 GeV	140 GeV
(a) $\delta y_{Hbb}/y_{Hbb}$	0.3 0.1	0.3 0.1	0.7 0.2
(b) $\delta y_{Hbb}/y_{Hbb}$	0.2 0.06	0.2 0.06	0.3 0.1

The results rely also on the assumption of $SU(2)$ invariance to relate the contributions from the HWW and HZZ couplings, which can not be experimentally disentagled in the WBF mechanism

Combining $qq \to qq(H \to b\bar{b})$ with $qq \to qq(H \to \tau^+\tau^-)$ allows a model independent determination of

$$\Gamma(H \to b\bar{b})/\Gamma(H \to \tau^+\tau^-)$$

to be confronted with what obtained in $t\bar{t}H$ production

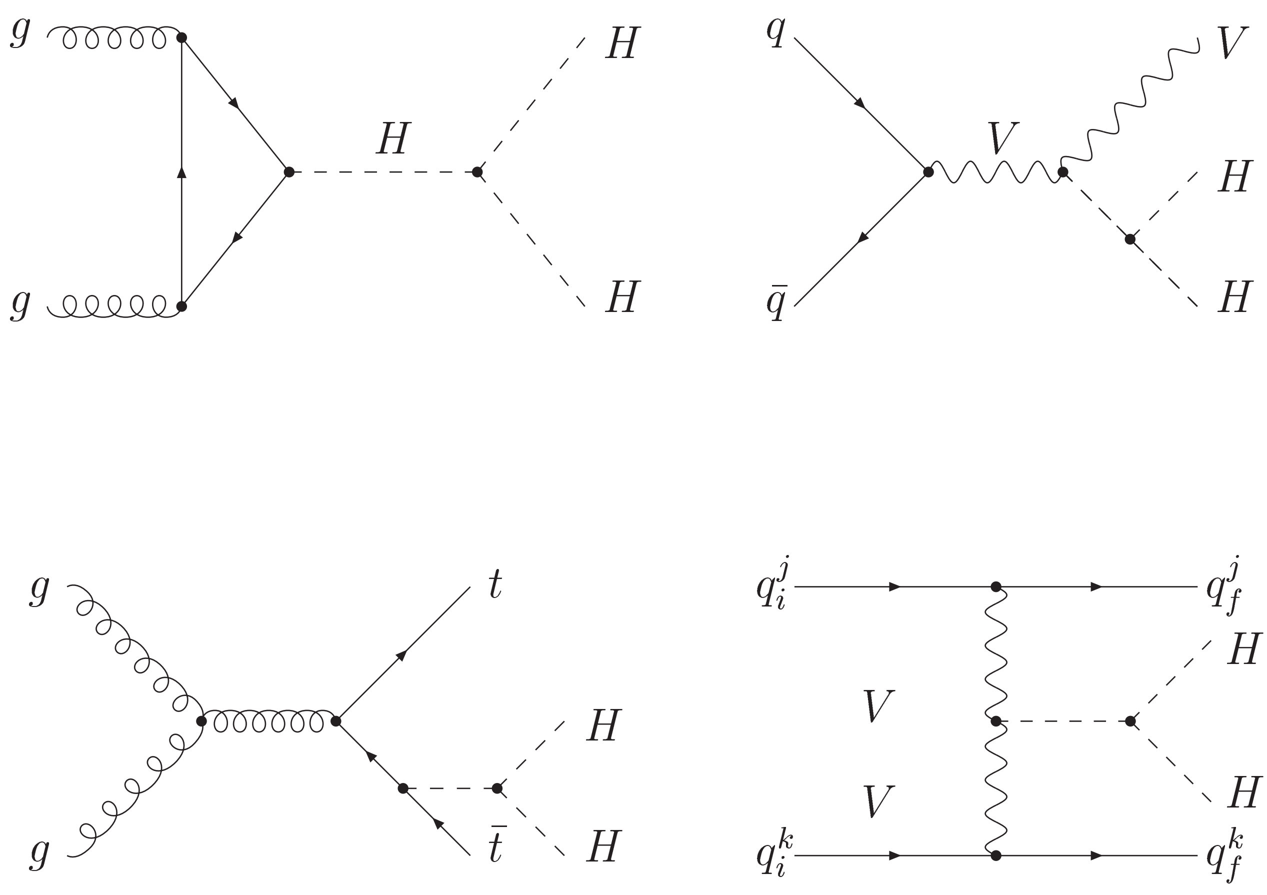
Comparing $qq \to qq(H \to b\bar{b})$ with the associated $W(H \to b\bar{b})$ production, another test of the SU(2) relation between HWW and HZZ couplings for low Higgs masses could be obtained

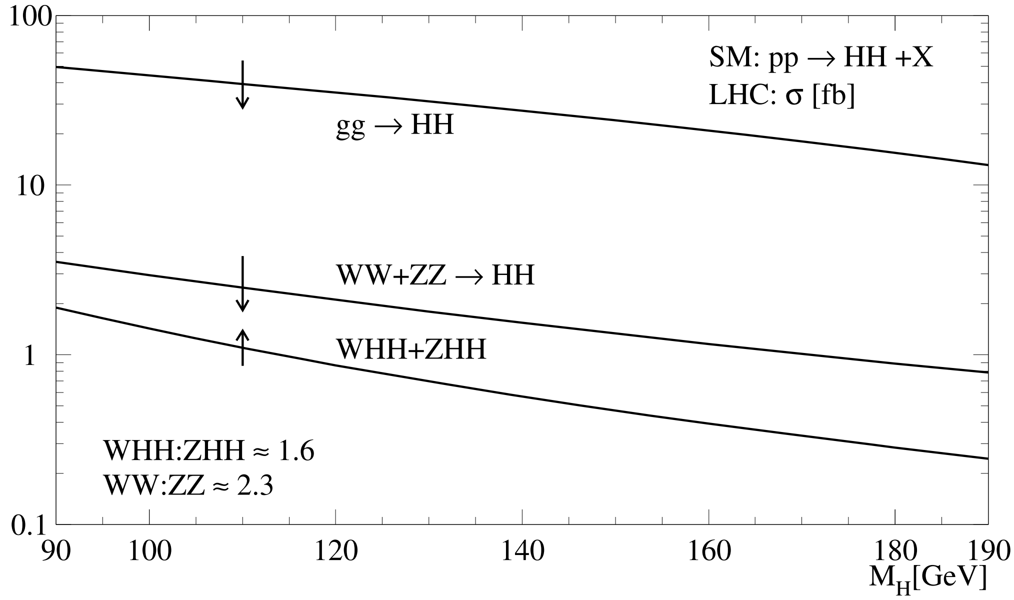
Higgs self-coupling

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 λ_{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, $gg \to HH$ 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:

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

The requirement of like-sign leptons essential to eliminate $t\bar{t}$ and Drell Yan backgrounds

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. $t\bar{t}t\bar{t}$

All these backgrounds are in principle reducible, since they share one or more of the following features not present in the signal:

- presence of b-jets
- presence of hard and isolated leptons
- jet-jet invariant masses not consistent with W decays

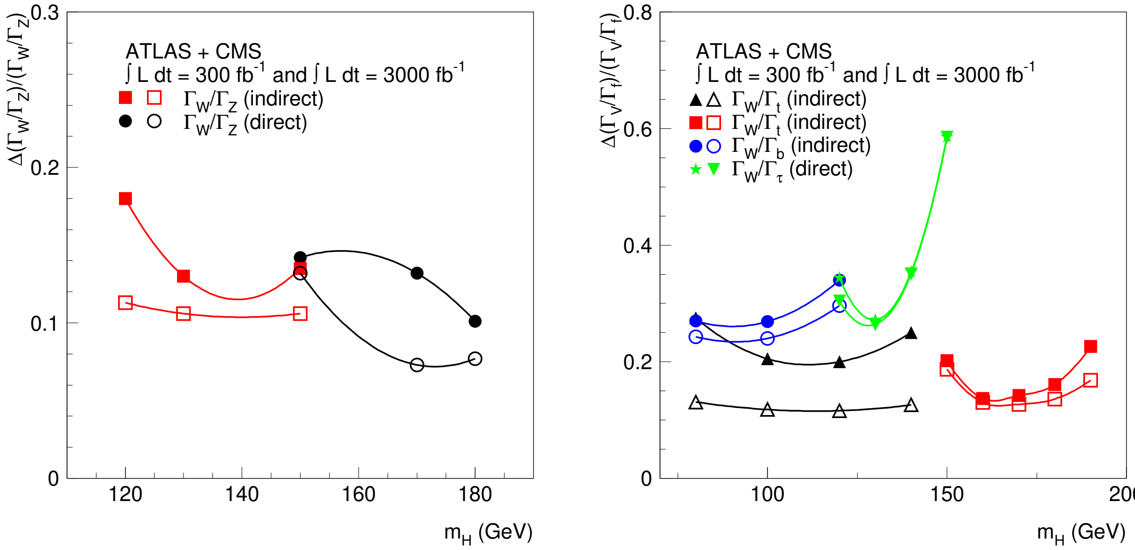
Selection criteria

- reweighting factor of 0.5 for each b jet with $E_T > 30$ GeV and $|\eta| < 2.4$
- at least two jet pairs with invariant masses $50 < m_{jj} < 110$ GeV
- ${p_T}^{\ell} >$ 20GeV , $|\eta_\ell| < 2.4 \quad \forall\, \ell$
- at least 4 jets with $E_T > 20$ GeV and $|\eta| < 2.4$, two of which with $E_T > 30$ GeV
- at most six jets with $E_T > 30$ GeV

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 λ_{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

- Many Higgs production and decay mechanisms are available at LHC, especially in the low mass region
- The Higgs mass can be directly measured with a precision of the order of 0.1% over all the entire spectrum
- The combination of several channels allows an indirect determination of the Higgs total width with a precision of 20–30% in the low mass region and even better for higher mass values, providing complemetary information to the direct measurement, which can be performed only for $m_H > 200$ GeV
- LHC will allow a model independent analysis of Higgs couplings to vector bosons and fermions at the 10–25% level for low Higgs mass.
- The $H \to b\bar{b}$ channel in WBF production, even if very challenging, will add important information on the $Hb\bar{b}$ Yukawa couling
- For $m_H > 140$ GeV the study of couplings to fermions becomes difficult
- Higgs self-coupling could 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 through the gluon fusion production channel