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Production of neutral Higgs-boson pairs at LHC

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Abstract. The reconstruction of the Higgs potential in the Standard Model or supersymmetric theories demands the measurement of the trilinear Higgs couplings. These couplings affect the multiple production of Higgs bosons at high energy colliders. We present a systematic overview of the cross sections for the production of pairs of (light) neutral Higgs bosons at the LHC. The analysis is carried out for the Standard Model and its minimal supersymmetric extension.

1 Introduction

1. Self-interactions of the Higgs field in the scalar sector induce the breaking of the electroweak symmetry $SU(2)_L \times U(1)_Y$ down to the electromagnetic symmetry $U(1)_{EM}$ of the Standard Model (SM). Gauge bosons and fermions acquire masses by interactions with the non-zero Higgs field $v = 1/(\sqrt{2}G_F)^{1/2}$ in the ground state of the scalar potential. It is therefore an important experimental task to reconstruct the elements of the Higgs potential which gives rise to the spontaneous breaking of the electroweak symmetry. The shape of the potential is determined by the mass M_H of the physical Higgs boson field, and its trilinear and quadrilinear couplings. The trilinear coupling [1],

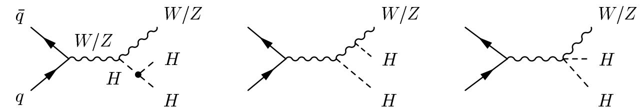
$$\lambda_{HHH} = 3M_H^2/M_Z^2 \tag{1}$$

in units of $\lambda_0 = M_Z^2/v$, can be measured directly in the production of Higgs-boson pairs at high energy colliders. In proton collisions at the LHC, Higgs pairs can be produced through double Higgs-strahlung off W and Z bosons [2], WW and ZZ fusion [3], and gluon-gluon fusion [4]; in generic notation:

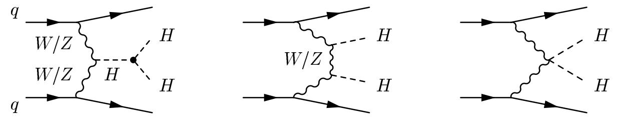
double Higgs-strahlung:
$$q\bar{q} \to W^*/Z^* \to W/Z + HH$$
WW/ZZ double-Higgs fusion:
$$qq \to qq + WW/ZZ \to HH$$
gluon fusion: $gg \to HH$

Characteristic diagrams of the three processes are shown in Fig. 1. With values typically near 10 fb, high integrated luminosities are needed to generate a sufficiently large ensemble of signal events and to cope with the large number of background events.

double Higgs-strahlung: $q\bar{q} \to ZHH/WHH$



WW/ZZ double-Higgs fusion: $qq \to qqHH$



gg double-Higgs fusion: $gg \to HH$

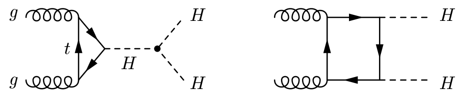
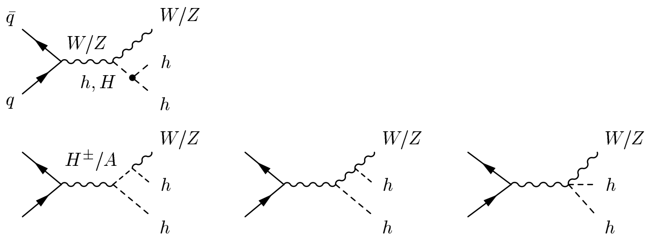
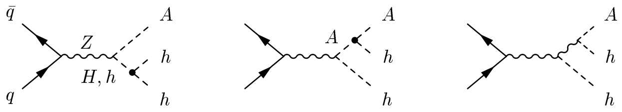


Fig. 1. Processes contributing to Higgs-pair production in the Standard Model at the LHC: double Higgs-strahlung, WW/ZZ fusion, and gg fusion (generic diagrams)

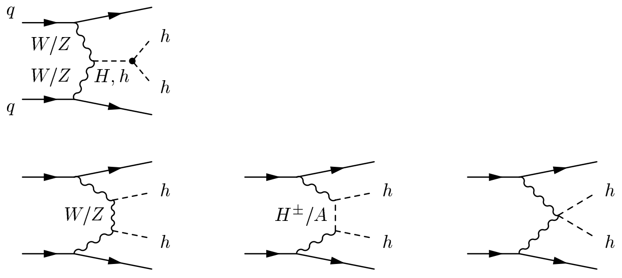
2. The Minimal Supersymmetric extension of the Standard Model (MSSM) incorporates a quintet of Higgs bosons: h, H, A, $H^{\pm}$; the particles h, H are neutral and CP-even while A is neutral and CP-odd. The mass of the light CP-even Higgs boson h is limited to less than about 130 GeV. The masses of the other Higgs bosons are typically of the order of the electroweak symmetry breaking scale v, yet they may extend up to values of order 1 TeV. The MSSM Higgs system is described inherently by two parameters which are generally chosen as the mass M_A of the pseudoscalar Higgs boson and the mixing parameter $\tan\beta$, ratio of the vacuum expectation values of the double Higgs-strahlung: $q\bar{q} \to Zhh/Whh$



triple Higgs production: $q\bar{q} \to Ahh$



WW/ZZ double-Higgs fusion: $qq \to qqhh$



gg double-Higgs fusion: $gg \to hh$

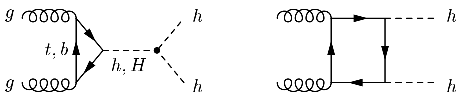


Fig. 2. Processes contributing to double and triple Higgs production involving trilinear couplings in the MSSM

two neutral Higgs fields. Radiative corrections introduce the mass and mixing parameters of the heavy $t/\tilde{t}$ and $b/\tilde{b}$ chiral multiplets into the system.

In CP-invariant theories, six types of trilinear couplings are realized among the neutral Higgs fields [1–5]:

$$hhh,\ Hhh,\ HHh,\ HHH$$
$$hAA,\ HAA$$

They can be expressed in terms of the two mixing angles β and α, mixing angle in the CP-even Higgs sector. The couplings involving two light Higgs bosons, for example, are given by the trigonometric functions

$$\begin{aligned}\lambda_{hhh} &= 3\cos 2\alpha \sin(\beta+\alpha) + 3\frac{\epsilon}{M_Z^2}\frac{\cos\alpha}{\sin\beta}\cos^2\alpha \qquad (2)\\ \lambda_{Hhh} &= 2\sin 2\alpha \sin(\beta+\alpha) - \cos 2\alpha \cos(\beta+\alpha)\\ &\quad + 3\frac{\epsilon}{M_Z^2}\frac{\sin\alpha}{\sin\beta}\cos^2\alpha\end{aligned}$$

cascade decay: $q\bar{q} \to AH/HH^\pm \to ZHh/WHh$

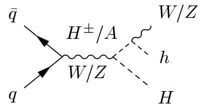


Fig. 3. Processes which contribute to double light plus heavy Higgs production in the MSSM but which do not involve trilinear couplings

The couplings are defined in units of λ_0. They are renormalized indirectly by the renormalization of the mixing angle α and directly by additive terms proportional to the radiative correction parameter ϵ which, to leading order, is given by $\epsilon = 3G_F M_t^4/(\sqrt{2}\pi^2 \sin^2\beta) \cdot \ln(M_{\tilde{t}}^2/M_t^2)$ [6]. In the subsequent numerical analysis the complete one-loop and the leading two-loop corrections to the Higgs masses and couplings [7] are included . The size of the couplings has been exemplified for a set of parameters in [1].

The trilinear MSSM Higgs couplings are involved in a large number of multi-Higgs processes at the LHC [8–9]:

double Higgs-strahlung:
$q\bar{q} \to W/Z + H_iH_j$ and $W/Z + AA$ $[H_{i,j} = h, H]$

triple Higgs production:
$q\bar{q} \to AH_iH_j$ and AAA

WW/ZZ double-Higgs fusion:
$qq \to qq + H_iH_j$ and $qq + AA$

gg fusion:
$gg \to H_iH_j,\ H_iA$ and AA

In this analysis we will restrict ourselves to a specific class of final states while a comprehensive description of all processes will be deferred to a subsequent report [10]; we will study final states involving two light Higgs bosons h:

$$\begin{aligned}&pp \to gg \to hh \qquad (3)\\ &pp \to Z/W + hh \quad \text{and} \quad A + hh\end{aligned}$$

They are generated either in the continuum or, for moderate values of $\tan\beta$, in cascade decays, too [11]:

$$H \to hh, \quad A \to Zh \quad \text{and} \quad H^\pm \to W^\pm h \qquad (4)$$

A set of typical diagrams is shown in Fig. 2. We will also present selected results on cascade decays involving heavy Higgs bosons H in the final state; they can be generated in the chains

$$\begin{aligned}&q\bar{q} \to Z^* \to AH \to ZHh \qquad (5)\\ &q\bar{q} \to W^* \to H^\pm H \to WHh\end{aligned}$$

These chains give rise to large rates, yet they do not involve trilinear Higgs couplings but only gauge couplings. The corresponding diagrams are shown in Fig. 3.

The cross sections for continuum production are generally small and it will be difficult to discriminate the signal from the background, after the decay of the Higgs particles into pairs of b quarks, for instance. Cascade decays, on the other hand, have been proposed to search for these particles at the LHC [12].

The present paper has got a limited goal. We have built up the general theoretical formalism for multiple Higgs production at the LHC in the Standard Model and the MSSM, and we discuss a few examples in detail, see also [10]. Just setting the base for these processes we do not intend to consider background reactions in a systematic way; such simulations can only be carried out by taking proper account of detector properties, what is beyond the scope of this paper.

2 Higgs pairs in the standard model

The cross sections for double Higgs-strahlung off W/Z bosons and for vector-boson fusion can be evaluated, *mutatis mutandis*, at the quark level for the LHC in the same way as for e^+e^- collisions, cf. [1]; just the couplings have to be adjusted properly. The proton cross sections are derived by folding the parton cross sections $\hat{\sigma}(qq' \to HH; \hat{s})$ of the quark subprocesses with the appropriate luminosities $d\mathcal{L}^{qq'}/d\tau$:

$$\sigma(pp \to HH) = \int_{4M_H^2/s}^{1} d\tau \frac{d\mathcal{L}^{qq'}}{d\tau} \hat{\sigma}(qq' \to HH; \hat{s} = \tau s) \tag{6}$$

where

$$\frac{d\mathcal{L}^{qq'}}{d\tau} = \int_{\tau}^{1} \frac{dx}{x} q(x; Q^2) q'(\tau/x; Q^2) \tag{7}$$

with q and q' denoting the parton densities in the proton [13], taken at a typical scale $Q \sim M_H$.

The large number of gluons in high-energy proton beams provides an additional mechanism for the production of Higgs pairs: gluon fusion $gg \to HH$ [4]. The proton cross section is derived by folding the parton cross section $\hat{\sigma}(gg \to HH)$ with the gluon luminosity. The coupling between gluons and SM Higgs bosons is mediated by heavy top-quark loops. As expected from single Higgs production [14], QCD radiative corrections are particularly important for this channel. They have been determined in the low-energy limit of small Higgs masses $M_H^2 \ll 4M_t^2$, leading to a K factor $K \approx 1.9$ [15]. A K factor of similar size is generally expected for Higgs masses beyond the top-quark threshold.

The cross sections are shown in Fig. 4 for the intermediate Higgs mass range discussed above. Gluon fusion dominates over the other mechanisms. The WW/ZZ fusion mechanisms are the next important channels. In addition to the four b jets, the four $WW^{(*)}WW^{(*)}$ bosons or the mixed $bbWW^{(*)}$ pairs generated in the decays of the two Higgs bosons, the light-quark jets associated with the equivalent W/Z bosons in the fragmentation, $q \to W/Z+q$ can be exploited to tag fusion events; these jets are emitted at average transverse momenta $p_T \sim 1/2 M_{W/Z}$. WW fusion dominates over ZZ fusion at a ratio $WW{:}ZZ \approx 2.3$. The cross sections for double Higgs-strahlung are relatively small. This follows from the scaling behavior of the cross sections which drop $\sim 1/\hat{s}$. The cross sections for Higgs-strahlung off W and Z bosons are combined in Fig. 4; their relative size is close to $W/Z \approx 1.6$. The vertical arrows indicate the sensitivity of the cross sections to the size of the trilinear Higgs coupling; they correspond to a modification of the trilinear SM coupling λ_{HHH} by the *ad hoc* rescaling coefficient $\kappa = 1/2 \to 3/2$.

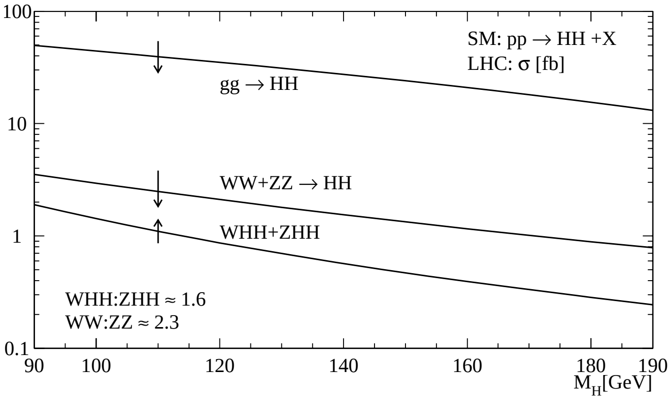


Fig. 4. The cross sections for gluon fusion, WW/ZZ fusion and double Higgs-strahlung WHH, ZHH in the SM. The vertical arrows correspond to a variation of the trilinear Higgs coupling from 1/2 to 3/2 of the SM value

3 Higgs pairs in supersymmetric theories

With appropriate modifications, the pattern of MSSM Higgs pair-production at the LHC is similar to the characteristics in e^+e^- collisions [1,5]. An important exception however is the additional gluon-fusion channel [9].

1. We will focus on the production of pairs of light Higgs bosons: $pp \to hh$. For moderate values of $\tan\beta$, the hh production channels follow the pattern of the Standard Model, with gluon fusion being dominant, Fig. 5a. However, within the cascade-decay regions of the heavy Higgs bosons H, $H^\pm$ the cross sections rise dramatically. These domains are marked in the figures explicitly by arrows. Large contributions to the cross sections are generated by heavy Higgs formation $gg/VV \to H \to hh$ in the fusion channels, and $H^\pm \to W^\pm h$ decay in Higgs-strahlung $W^{\pm *} \to H^\pm h \to W^\pm hh$. As expected [9], the gluon-fusion hh cross section becomes very large in the H decay region, giving rise to a sample of about a million hh events. This process therefore provides an important channel for searching for MSSM Higgs bosons at the LHC [12]. The sensitivity of the cross sections with regard to a variation of λ_{hhh} by the rescaling factor $\kappa = 1/2$ to $3/2$ is close to ten per-cent in the continuum while the sensitivity of H cascade decays to a variation of λ_{Hhh} is indicated by arrows.

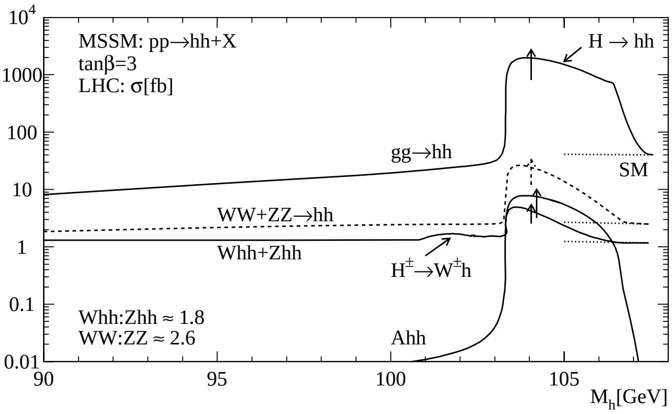


Fig. 5a. Total cross sections for MSSM hh production via double Higgs-strahlung Whh and Zhh, WW/ZZ fusion and gluon fusion at the LHC for $\tan\beta = 3$, including mixing effects ($A = 1$ TeV, $\mu = -1$ TeV)

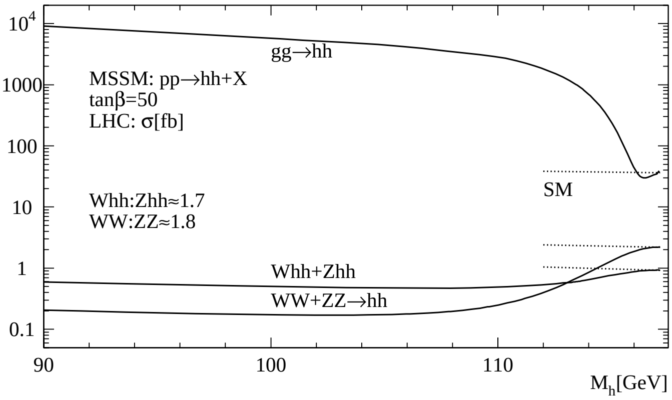


Fig. 5b. Total cross sections for MSSM hh production via double Higgs-strahlung Whh, Zhh, WW/ZZ fusion and gluon fusion at the LHC for $\tan\beta = 50$, including mixing effects ($A = 1$ TeV, $\mu = 1$ TeV)

For large $\tan\beta$, a huge ensemble of hh continuum events is generated by gluon fusion, Fig. 5b. The enhancement is due to the large hbb Yukawa coupling, $\sim m_b \tan\beta$, in the b-quark loops connecting the gluons with the Higgs bosons. Since the box diagrams are enhanced quadratically compared to the triangle diagrams, the sensitivity to the trilinear coupling is small.[1] The continuum cross sections of the VV fusion and Higgs-strahlung channels are suppressed with respect to the Standard Model until the decoupling limit is reached. For large $\tan\beta$ cascade decays do not play a role in hh pair production; the kinematical decay thresholds are reached only for masses for which the decoupling limit is being approached.

2. Two processes involve Higgs-pair final states including a light plus a heavy Higgs boson. However for cross sections in excess of 1 fb, Fig. 6, the final states are generated in cascade decays by gauge interactions:

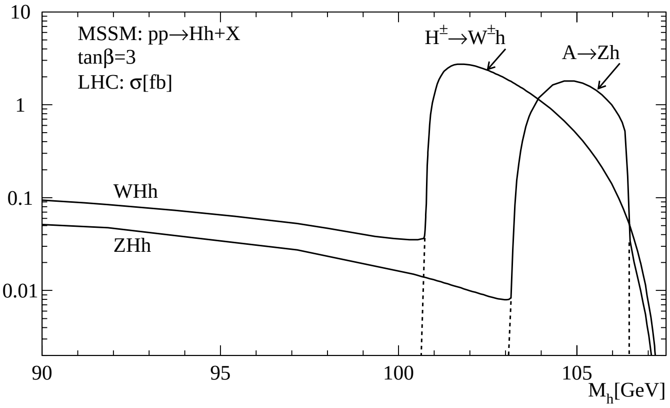


Fig. 6. Total cross sections for MSSM Hh production in the processes WHh and ZHh for $\tan\beta = 3$, including mixing effects ($A = 1$ TeV, $\mu = -1$ TeV)

$$\begin{aligned} pp &\xrightarrow[Z]{} AH \to ZHh \\ pp &\xrightarrow[W]{} H^{\pm}H \to W^{\pm}Hh \end{aligned} \tag{8}$$

These processes are therefore not suitable for measuring trilinear Higgs couplings.

4 Conclusions

In the present paper we have analyzed the production of neutral Higgs-bosons pairs in various channels at the LHC which can eventually be used to measure fundamental trilinear Higgs self-couplings. In a first step we have compared the production cross sections in the Standard Model, assuming a Higgs-boson mass in the intermediate range. Moreover, we have calculated the cross sections for pairs of light Higgs bosons in the Minimal Supersymmetric extension of the Standard Model. Earlier results have been combined with new calculations in these analyses.

The continuum cross sections are generally small in the SM and MSSM, yet not for gluon fusion. The trilinear SM Higgs coupling and the trilinear coupling λ_{hhh} in the MSSM may thus be accessible experimentally, provided the backgrounds can be rejected sufficiently well. If Higgs cascade decays $H \to hh$ occur in the MSSM, they can be exploited to measure one of the couplings between light and heavy CP-even neutral Higgs bosons, λ_{Hhh}.

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