PROCEEDINGS OF SCIENCE

Signal-background interference in $gg \to H \to VV$

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The resonance-continuum interference between the SM Higgs search signal process $gg \to H \to VV$ ($V = W, Z$) and the irreducible background process $gg \to VV$ is studied at leading order for integrated cross sections and differential distributions in pp collisions at $\sqrt{s} = 7$ TeV and 14 TeV for $M_H = 400$ GeV. Leptonic weak boson decays are included, and realistic experimental selection cuts are applied.

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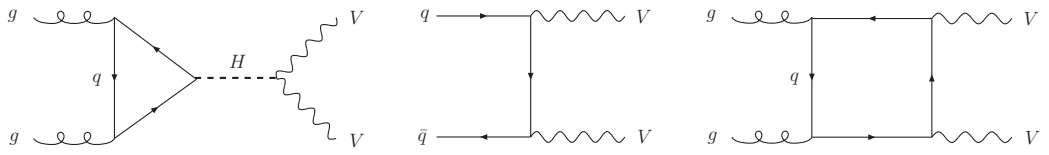

Figure 1: Representative Feynman graphs for the Higgs signal process (left) and the $q\bar{q}$- (centre) and gg-initiated (right) continuum background processes at LO.

1. Introduction

Higgs production in gluon fusion with subsequent decay into a weak boson pair is an important element of the Higgs search at the LHC. The signal process (Fig. 1, left) has been calculated and studied up to NNLO (see Refs. [1 – 11] and references therein). Continuum weak boson pair production is the dominant irreducible background and has also been studied extensively. For the leading quark scattering subprocess (Fig. 1, centre), programs at NLO are available, in part based on earlier calculations (see Refs. [12 – 14] and references therein). Here, we focus on the gluon scattering subprocess (Fig. 1, right) and its interference with the signal process. $gg \to VV$ continuum production formally enters at NNLO and was calculated in Refs. [15 – 18]. Off-shell weak boson decays and the possibility to interface with shower programs were subsequently included [13, 19 – 25]. At the LHC, the importance of gluon-induced VV continuum production and decay is enhanced by the large gluon-gluon flux and experimental Higgs search selection cuts. Resonance-continuum interference has been studied for $gg\ (\to H) \to VV$ in Refs. [11, 16, 17, 22, 24, 26] and for related processes in Refs. [27 – 29]. Here, results for a heavy Higgs boson with $M_H = 400$ GeV are presented. The search for a heavy Higgs boson at hadron colliders has been examined in Refs. [30 – 33].

2. Calculational details

The results presented in Section 3 have been calculated with the programs gg2WW [20, 22] and gg2ZZ [23]. Representative graphs for the $gg \to H \to VV$ signal process and the $gg \to VV$ continuum process are displayed in Fig. 1. In addition to box topologies in principle also triangle topologies contribute to the gg-initiated continuum processes (see Fig. 2). But, in the limit of vanishing lepton masses the triangle graphs do not contribute.[1] For cross checks, two amplitude codes have been used based on the methods described in Ref. [22] (BCKK) and Refs. [34, 35] (FormCalc). Off-shell weak boson contributions and massless as well as massive quarks are taken into account. Third quark generation contributions increase the total $gg \to WW \to$ leptons continuum cross section by 12% and the double-resonant $gg \to ZZ \to$ leptons continuum cross section by 65% (pp, $\sqrt{s} = 14$ TeV). For Z-pair production and decay, the γ^* contributions are taken into account. For W-pair production and decay, the BCKK code approximates $V_{\text{CKM}} = 1$. The FormCalc code was used to confirm at the amplitude level that this is an excellent approximation as CKM effects

[1] Note that the $gg \to Z$ triangle graphs do contribute for non-zero lepton masses, which was verified by explicit calculation.

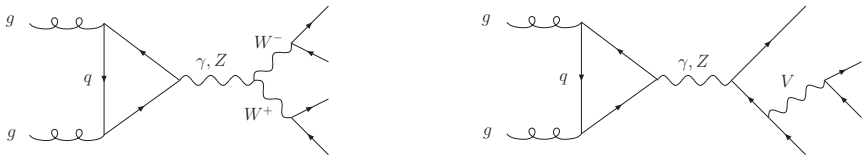

Figure 2: Representative triangle graphs that formally contribute to gluon-induced VV continuum production and decay.

are smaller than 0.01%. The gg2VV programs allow for the simultaneous calculation of cross sections for multiple scales as well as the PDF error.[2]

As both amplitude implementations employ Passarino-Veltman-type tensor integral reduction methods, a discussion of numerical stability is warranted. The box amplitudes are affected by spurious singularities, which are caused by inverse powers of the Gram determinant $\det G = 2s(tu - M_{V_1^*}^2 M_{V_2^*}^2)$, because $\det G \to 0$ as $p_{TV} \to 0$. For phenomenologically relevant cross sections, the error caused by numerical instabilities should be small compared to practical MC integration errors, which are typically of order 0.1%. After the symbolic cancellation of Gram determinants, the BCKK amplitude code evaluated in quadruple precision is numerically stable in the above sense.[3] On the other hand, numerical instability is observed for the FormCalc amplitude code when evaluated in quadruple precision for a relevant phase space (PS) configuration with $p_{TV} = 0.007$ GeV. Using the stable BCKK code as benchmark, the following diagnostic algorithm was devised to detect problematic PS points with the FormCalc code and quadruple precision: First, we exploit that instabilities spoil Lorentz invariance by comparing $|\mathscr{M}|^2$ evaluated at the PS point and the PS point boosted along the beam axis with $p_{\text{boost}} = (1,0,0,0.001 + 0.1\,r_1)$ GeV with random $r_1 \in [0,1]$.[4] The relative deviation is assessed using $\text{reldev}(x,y) = |x-y|/\min(x,y)$. If $\text{reldev}(|\mathscr{M}|^2, |\mathscr{M}_{\text{boosted}}|^2) > 10^{-4}$ the PS point is classified as unstable. The same criterion is then applied again, except now with a random boost in the opposite direction. If the PS point is still considered stable another test is performed, which exploits that instabilities occur at exceptional PS configurations. One therefore compares $|\mathscr{M}|^2$ evaluated at the PS point (in double precision) and the PS point mapped to single precision. If $\text{reldev}(|\mathscr{M}|^2, |\mathscr{M}_{\text{single}}|^2) > 1$ the PS point is classified as unstable. Unstable PS points are discarded. Only in combination allow these tests to detect all instabilities. As indicated above, this has been verified by comparison with the stable BCKK code. One can thus also assess the error introduced by discarding PS points that are wrongly classified as unstable. The parameters have been adjusted to minimize this error. For integrated cross sections, it is approximately 0.03%.

[2] Sample output: scale1: 10.5817 MC: ±0.0063 (±0.059%) scale(×2): −2.5573 (−24%) +3.6967 (+35%) PDF: −0.2723 (−2.6%) + 0.2382 (+2.3%) fb, sym. scale error: ±28%, sym. PDF error: ±2.4%, scale2: 19.121 MC: ±0.012 (±0.061%) fb

[3] Differential distributions are smooth, even when calculating extreme cross sections like $\sigma(p_{TV} < 1\text{ GeV})$.

[4] The PS point is assumed to be given in the rest frame of p_{boost}. The PS point is boosted to the frame in which p_{boost} is given.

		σ [fb], pp, $\sqrt{s} = 7$ TeV, $M_H = 400$ GeV			interference	
process	cuts	$\lvert\mathscr{M}_H\rvert^2$	$\lvert\mathscr{M}_{\text{cont}}\rvert^2$	$\lvert\mathscr{M}_H + \mathscr{M}_{\text{cont}}\rvert^2$	R_1	R_2
$gg\ (\to H) \to WW$	stand.	4.361(3)	6.351(4)	10.582(7)	0.9879(8)	0.970(2)
$gg\ (\to H) \to WW$	Higgs	2.502(2)	0.633(1)	3.007(3)	0.959(2)	0.949(2)
$gg\ (\to H) \to ZZ$	stand.	0.3654(4)	0.3450(4)	0.7012(8)	0.987(2)	0.975(3)
$gg\ (\to H) \to ZZ$	Higgs	0.2729(3)	0.01085(2)	0.2867(3)	1.010(2)	1.011(2)

Table 1: Cross sections in fb for $gg\ (\to H) \to W^-W^+ \to l\bar{\nu}_l\bar{l}'\nu_{l'}$ and $gg\ (\to H) \to ZZ \to l\bar{l}l'\bar{l}'$ in pp collisions at $\sqrt{s} = 7$ TeV for $M_H = 400$ GeV and a single lepton flavour combination calculated at LO. Standard cuts and Higgs search cuts are applied (see main text). Interference effects are illustrated through $R_1 = \sigma(\lvert\mathscr{M}_{\text{VV}}\rvert^2)/\sigma(\lvert\mathscr{M}_H\rvert^2 + \lvert\mathscr{M}_{\text{cont}}\rvert^2)$ and $R_2 = \sigma(\lvert\mathscr{M}_H\rvert^2 + 2\,\text{Re}(\mathscr{M}_H\mathscr{M}_{\text{cont}}^*))/\sigma(\lvert\mathscr{M}_H\rvert^2)$.

3. Results

Parton-level cross sections for $gg\ (\to H) \to W^-W^+ \to l\bar{\nu}_l\bar{l}'\nu_{l'}$ and $gg\ (\to H) \to ZZ \to l\bar{l}l'\bar{l}'$ (l: charged lepton) in pp collisions at $\sqrt{s} = 7$ TeV are presented in Table 1. Results are given for a single lepton flavour combination, e.g. $l = e^-, l' = \mu^-$. Lepton masses are neglected. The input parameter set of Ref. [36], App. A, is used with NLO Γ_V and G_μ scheme. For the Higgs resonance, we set $M_H = 400$ GeV and $\Gamma_H = 29.16$ GeV [37]. The renormalisation and factorisation scales are set to $M_H/2$. The PDF set MSTW2008LO with 1-loop running for $\alpha_s(\mu^2)$ and $\alpha_s(M_Z^2) = 0.13939$ is used. The fixed-width prescription is used for Higgs and weak boson propagators. For ZZ production and decay, the virtual photon contributions have been included.

The following experimental selection cuts are adopted [36, 38]: As WW standard cuts, we use $p_{Tl} > 20$ GeV, $|\eta_l| < 2.5$, $\not{p}_T > 30$ GeV and $M_{l\bar{l}'} > 12$ GeV. As WW Higgs search cuts for $M_H = 400$ GeV, we use the WW standard cuts and in addition $p_{Tl,\text{min}} > 25$ GeV, $p_{Tl,\text{max}} > 90$ GeV, $M_{l\bar{l}'} < 300$ GeV and $\Delta\phi_{l\bar{l}'} < 175^\circ$. As ZZ standard cuts, we use $p_{Tl} > 20$ GeV, $|\eta_l| < 2.5$ and 76 GeV $< M_{l\bar{l}}, M_{l'\bar{l}'} < 106$ GeV. As ZZ Higgs search cuts, we use the ZZ standard cuts and in addition $|M_{l\bar{l}l'\bar{l}'} - M_H| < \Gamma_H$.

The significance of a Higgs or new physics observation is determined as function of the number of signal events $S \propto \sigma(\lvert\mathscr{M}_{\text{sig}}\rvert^2)$ and background events $B \propto \sum\sigma(\lvert\mathscr{M}_{\text{bkg}}\rvert^2)$. When signal and background interfere the distinction becomes blurred. Here: $\lvert\mathscr{M}_{\text{VV}}\rvert^2 = \lvert\mathscr{M}_H\rvert^2 + \lvert\mathscr{M}_{\text{cont}}\rvert^2 + 2\,\text{Re}(\mathscr{M}_H\mathscr{M}_{\text{cont}}^*)$. One can choose to include the interference term in the signal: $S_i \propto \sigma(\lvert\mathscr{M}_H\rvert^2 + 2\,\text{Re}(\mathscr{M}_H\mathscr{M}_{\text{cont}}^*))$.[5] We assess interference effects using two measures: $R_1 = \sigma(\lvert\mathscr{M}_{\text{VV}}\rvert^2)/\sigma(\lvert\mathscr{M}_H\rvert^2 + \lvert\mathscr{M}_{\text{cont}}\rvert^2)$ and $R_2 = \sigma(\lvert\mathscr{M}_H\rvert^2 + 2\,\text{Re}(\mathscr{M}_H\mathscr{M}_{\text{cont}}^*))/\sigma(\lvert\mathscr{M}_H\rvert^2)$. As shown in Table 1, at $\sqrt{s} = 7$ TeV interference effects can be as large as 5%. At $\sqrt{s} = 14$ TeV, interference effects can approach the 10% level: for WW production and standard cuts (Higgs search cuts) one obtains $R_1 = 0.9680(8)$ ($R_1 = 0.940(2)$) and $R_2 = 0.932(2)$ ($R_2 = 0.926(2)$), and for ZZ production and standard cuts (Higgs search cuts) one obtains $R_1 = 0.969(2)$ ($R_1 = 1.011(2)$) and $R_2 = 0.945(3)$ ($R_2 = 1.011(3)$). While the additional Higgs search cuts increase the negative interference for WW production, for ZZ production the $|M_{l\bar{l}l'\bar{l}'} - M_H| < \Gamma_H$ cut limits the interference effect to about 1%. The latter

[5] In principle, S_i can be negative, and this does affect phenomenologically relevant distributions [24].

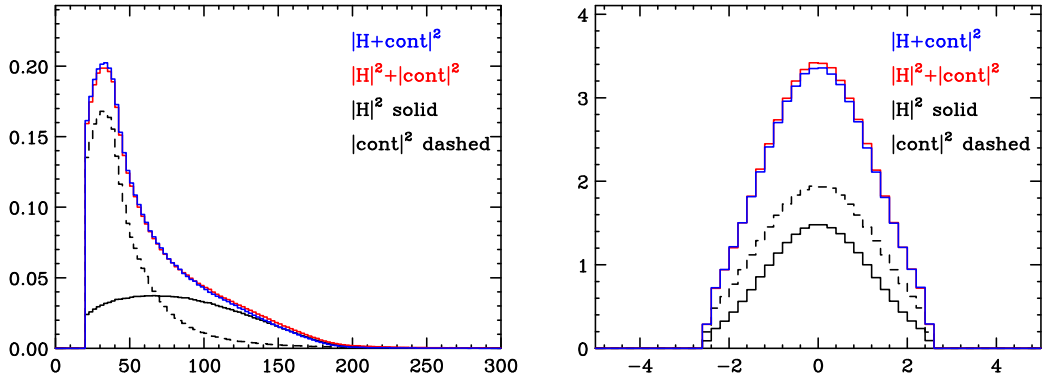

Figure 3: Differential cross section distributions for $gg\ (\to H) \to W^-W^+ \to l\bar{\nu}_l\bar{l'}\nu_{l'}$ in pp collisions at $\sqrt{s} = 7$ TeV for $M_H = 400$ GeV and a single lepton flavour combination calculated at LO. The p_{Tl} [GeV] (left) and η_l (right) distributions are shown. Standard cuts are applied (see main text). fb is used as cross section unit.

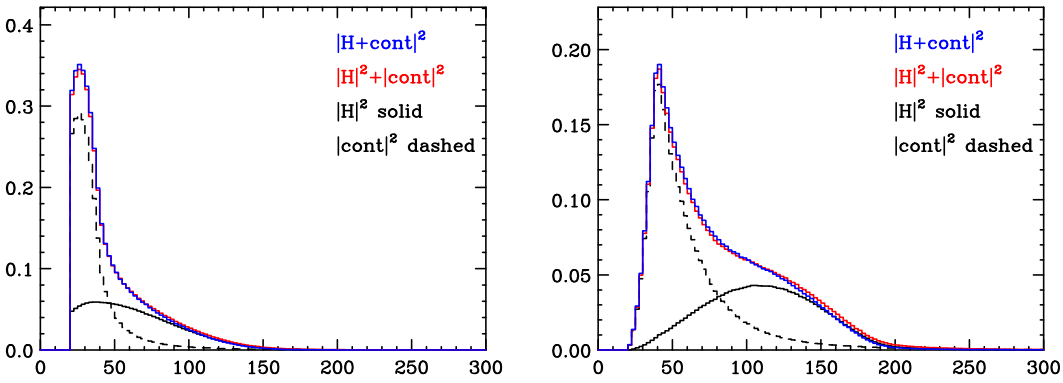

Figure 4: $p_{Tl,\mathrm{min}}$ [GeV] (left) and $p_{Tl,\mathrm{max}}$ [GeV] (right) distributions. Other details as in Fig. 3.

traces back to the fact that the interference changes sign at $M_{l\bar{l}l'\bar{l}'} = M_H$, as seen in Fig. 6 (left).

Differential distributions for phenomenologically relevant observables are shown in Figs. 3, 4 and 5 for WW production and in Fig. 6 for ZZ production. The distributions demonstrate that a compensation of positive and negative interference occurs for cross sections that are integrated over most of the phase space. For this reason, the more exclusive selection cuts typically used in Higgs and new physics searches can increase the size of the interference effects.

4. Conclusions

$gg\ (\to H) \to VV$ interference effects are not suppressed and can range from 1% to about 10%. They can be enhanced by Higgs search selection cuts and should be taken into account in the LHC data analysis.

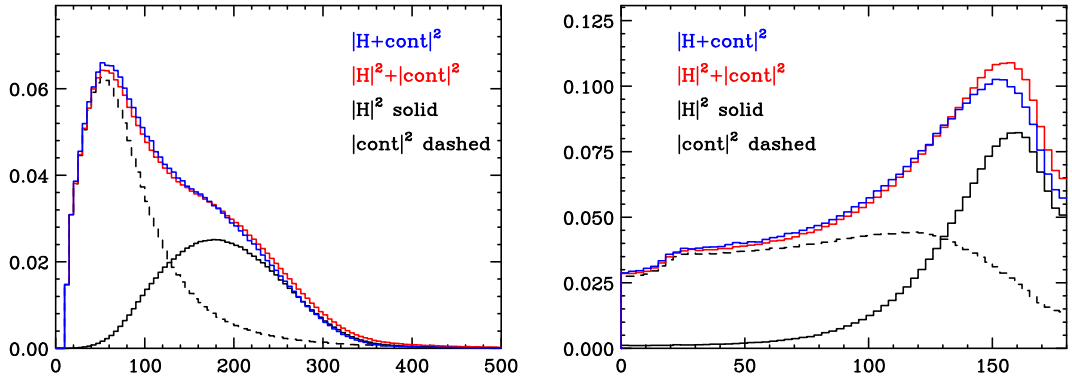

Figure 5: $M_{l\bar{l}'}$ [GeV] (left) and $\Delta\phi_{l\bar{l}'}$ [°] (right) distributions. Other details as in Fig. 3.

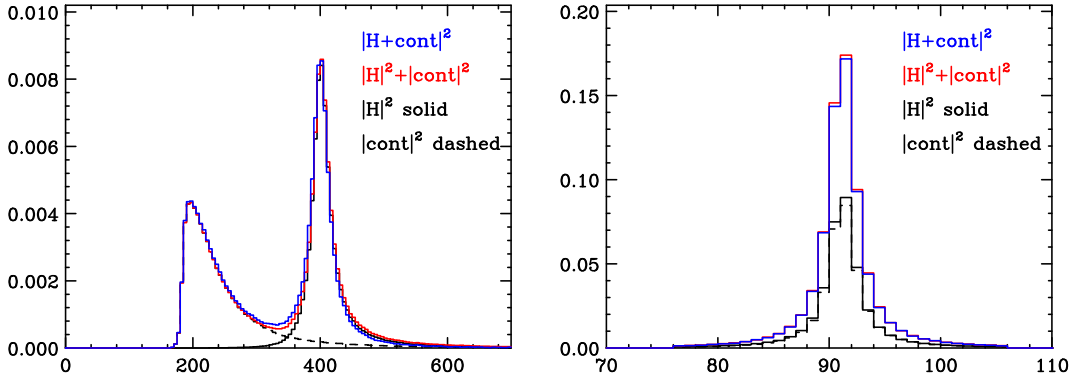

Figure 6: Differential cross section distributions for $gg\ (\to H) \to ZZ \to l\bar{l}l'\bar{l}'$ in pp collisions at $\sqrt{s} = 7$ TeV for $M_H = 400$ GeV and a single lepton flavour combination calculated at LO. The $M_{l\bar{l}l'\bar{l}'}$ [GeV] (left) and $M_{l\bar{l}'}$[GeV] (right) distributions are shown. Standard cuts are applied (see main text). fb is used as cross section unit.

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