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Supersymmetric Higgs Production in Vector-Boson Fusion

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We present a full calculation of the supersymmetric NLO corrections to Higgs boson production via vector-boson fusion. The supersymmetric QCD corrections turn out to be significantly smaller than the electroweak ones. These higher-order corrections are an important ingredient to a precision analysis of the Higgs sector at the LHC.

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1. Introduction

Understanding the origin of electroweak symmetry breaking is one of the main tasks of the Large Hadron Collider (LHC). Electroweak precision data predicts a light Higgs boson. To solve the hierarchy problem the Standard Model (SM) needs to be embedded in a larger theory for an ultra-violet completion. The Minimal Supersymmetric Standard Model (MSSM) is a very promising candidate for that. Higgs-boson production in vector-boson fusion with a subsequent decay of the Higgs into a pair of tau leptons is one of the most auspicious channels for an early discovery [1, 2]. The discovery reach for this channel covers the entire MSSM parameter space [3].

Determining the relations in the Higgs sector, like the gauge and Yukawa couplings [4], will then be the next step for the LHC. These measurements require a good knowledge of the associated rates and their theory errors need to be under control, including higher-order effects. The next-to-leading-order QCD corrections to vector-boson-fusion Higgs production are fairly small, of the order of ten percent [5]. This is due to the color structure of the process which forbids gluon exchange between the two quark lines, combined with its forward-jet nature. The electroweak corrections turn out to be of similar size and have opposite sign for the phenomenologically relevant region of a light Higgs boson [6]. Also the gluon-induced NNLO-QCD effects [7] and the interference between vector-boson-fusion and gluon-fusion Higgs production [8] have been investigated and found to be tiny.

For the MSSM these calculations must be augmented by the corrections originating from the additional supersymmetric particles and the extended Higgs sector. They need to be included for the determination of the Higgs sector, either as correction or as a theory uncertainty for early running or if the MSSM spectrum is not favorable to precision MSSM analyses [9]. Both cases need a detailed study of the supersymmetric contributions to vector-boson fusion [10, 11] and also gluon-fusion Higgs production [12].

2. Corrections in the MSSM Higgs sector

The coupling of the light supersymmetric Higgs to vector bosons receives an additional factor $\sin(\beta-\alpha)$ compared to its SM counter part, where $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets and α the mixing angle turning the two CP-even degrees of freedom into mass eigenstates. Hence for a given Higgs mass we obtain the tree-level MSSM cross section by simply rescaling the SM rate with $\sin^2(\beta-\alpha)$. For pseudoscalar Higgs masses m_A exceeding 200 GeV this factor is close to one. At next-to-leading order two additional types of diagrams appear: First, there are the ones where the SM particles in the loop are replaced by their supersymmetric counterparts. As we assume R parity conservation, a loop consists purely of either SM or supersymmetric particles. This allows for a diagrammatic separation of the new MSSM contributions. Second, contributions from the extended Higgs sector of the MSSM appear. As there is no one-to-one correspondence of the Standard-Model Higgs to an MSSM particle, we cannot separate them at the diagram level. Instead, we compute the full MSSM-Higgs corrections at the amplitude level and then subtract the SM Higgs part, multiplied by the tree-level correction factor. Since both the full MSSM and the SM are gauge-invariant, our supersymmetric corrections calculated in that way share this feature.

The large number of diagrams requires us to use automated tools for the evaluation. We compute the cross section with HadCalc [13] using the MRST 2002 NLO pdf set [14], where we have generated the Feynman diagrams and amplitudes with FeynArts and FormCalc [15]. The evaluation of the loop integrals we perform with LoopTools [16]. For an optimal mapping of the phase-space integration we use code from VBFNLO [17]. We assume minimal flavor violation, whose effect is small after taking all experimental and theoretical constraints into account [18], as well as a *CP*-conserving MSSM.

The mass of the lightest Higgs boson receives large loop corrections [19, 20, 21, 22], which push its value beyond the limits from LEP2 [23]. Therefore, we need to include them for a phenomenologically relevant analysis. Linked to the mass shift are corrections to the Higgs couplings [24], which we should add at the same order in perturbation theory. For the numerical evaluation of the Higgs sector we use FeynHiggs 2.6.2 [20]. We have checked that the differences to a program using the effective-potential approach [22] are small [11].

Consistent with FeynHiggs, we perform the renormalization of the Higgs sector including $\tan\beta$ in the $\overline{\mathrm{DR}}$ scheme. According to the LSZ prescription we then need to add finite wave-function renormalization terms to ensure that the residue of the Higgs boson pole is unity. We include them as an additional one-loop correction with the amplitude

$$\Gamma = (\sqrt{Z_{hh}} - 1)\Gamma_{h_0} + \sqrt{Z_{hh}} Z_{hH} \Gamma_{H_0} \,, \tag{2.1}$$

where Γ_{h_0} and Γ_{H_0} are the tree-level amplitudes for vector-boson-fusion h^0 and H^0 production, respectively. We use

$$\sqrt{Z_{hh}} = 1 - \frac{1}{2}\,\mathrm{Re}\left(\frac{\mathrm{d}}{\mathrm{d}p^2}\hat{\Sigma}_{hh}(p^2)\right)\bigg|_{p^2=m^2_{h^0}} \tag{2.2}$$

$$Z_{hH} = \frac{1}{m^2_{H^0} - m^2_{h^0}}\mathrm{Re}(\hat{\Sigma}_{hH}(m_{h^0})) \tag{2.3}$$

where the $\hat{\Sigma}$ are the renormalized one-loop self energies [20] and the Higgs boson masses are loop-corrected. All Standard-Model parameters are renormalized on-shell.

For our numerical analysis we require the following standard vector-boson-fusion cuts:

$$\begin{gathered} y_j < 4.5 \,, \qquad (p_T)_j > 20 \text{ GeV} \,, \qquad y_{j_1} \cdot y_{j_2} < 0 \,, \\ |y_{j_1} - y_{j_2}| > 4.5 \,, \qquad m_{\mathrm{inv}}(j_1, j_2) > 600 \text{ GeV} \,. \end{gathered} \tag{2.4}$$

3. Supersymmetric corrections

In Fig. 1 we show an example set of one-loop Feynman diagrams which appear in our calculation. We also include diagrams where the Higgs is radiated off the quark lines or the weak bosons are replaced by photons. The numerical results we first show for the parameter point SPS1a [25], where we have used the high-scale definition and evolved them to the low scale using SoftSUSY 2.0.14 [26]. The electromagnetic coupling constant we choose at vanishing momentum. Also we neglect all masses of the first two quark and lepton generations. The spectrum of this parameter point consists of fairly light particles with masses of uncolored particles typically at $100 - 200$ GeV

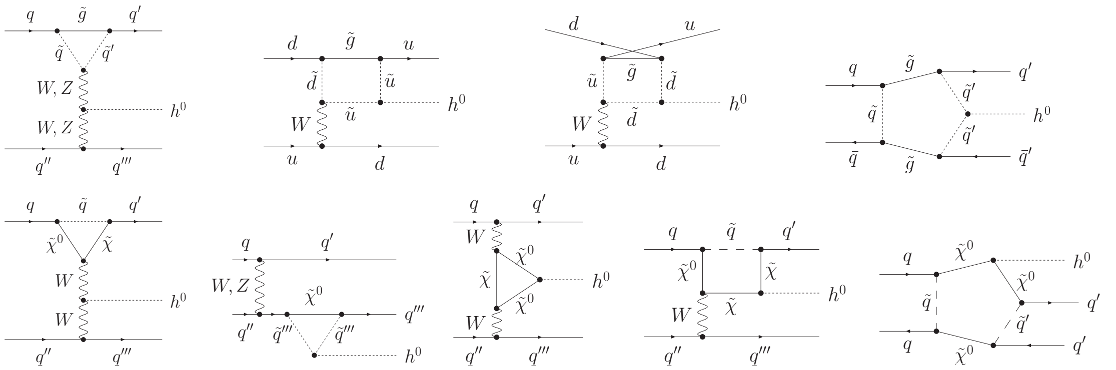

Figure 1: Example Feynman diagrams contributing to QCD (upper) and electroweak (lower) vertex corrections, boxes and pentagons.

diagram	$\Delta\sigma/\sigma$ [%]	$\Delta\sigma/\sigma$ [%]
	$\Delta\sigma \sim \mathcal{O}(\alpha)$	$\Delta\sigma \sim \mathcal{O}(\alpha_s)$
self energies	0.199	
$qq'W + qqZ$	-0.392	-0.0148
qqh	-0.0260	0.00545
$WWh + ZZh$	-0.329	
box	0.0785	-0.00518
pentagon	0.000522	-0.000308

sum of all $\Delta\sigma/\sigma = -0.484$ %

	$\Delta\sigma/\sigma$ [%]			
	VVh	$\mathcal{O}(\alpha)$	$\mathcal{O}(\alpha_s)$	all
SPS1a	-0.329	-0.469	-0.015	-0.484
SPS1b	-0.162	-0.229	-0.006	-0.235
SPS2	-0.147	-0.129	-0.002	-0.131
SPS3	-0.146	-0.216	-0.006	-0.222
SPS4	-0.258	-0.355	-0.008	-0.363
SPS5	-0.606	-0.912	-0.010	-0.922
SPS6	-0.226	-0.309	-0.010	-0.319
SPS7	-0.206	-0.317	-0.006	-0.323
SPS8	-0.157	-0.206	-0.004	-0.210
SPS9	-0.094	-0.071	-0.003	-0.074

Table 1: Complete MSSM corrections to the process $pp \to qqh$ by diagram types for the parameter point SPS1a (left) and for all SPS points (right). Tables taken from Ref. [11].

and squarks and gluinos around $500-600$ GeV, and $\tan\beta = 10$ leading to only small decoupling effects in the down-sector. We have compared our results to Ref. [10], where the vertex-correction contributions of the upper-left diagram of Fig. 1 have already been evaluated in the limit of equal squark masses, as well as to an upcoming second calculation of these corrections [27]. In both cases we find good agreement.

All supersymmetric QCD corrections turn out to be very small as we can see in Table 1. We find an even bigger suppression than in the Standard Model, where gluon exchange between the two quark lines leads to a vanishing color trace.

Two tree-level vertices receive one-loop corrections, qqV and VVh. Only at the first one squark/gluino loops appear. Since the W boson couples only to left-handed particles and the mixing between left- and right-handed light-flavor squarks is negligible, like at tree-level both external quarks are then left-handed. Therefore, the gluino propagator in the fermion trace can only contribute via its momentum and not via a gluino-mass insertion which would require a chirality flip. Hence the typical scale in the numerator is $m_h/2$, an order of magnitude below the gluino mass in the denominator.

In the electroweak case, also the lighter charginos and neutralinos in the loop couple to the vector boson. This means that we can add a double mass insertion into the fermion line which can partly compensate for the heavy masses in the loop denominator. This effect leads to a relative enhancement of the electroweak over the QCD qqV vertex correction we observe in Table 1.

In both box diagrams shown in the upper line of Fig. 1 the $\tilde{q}\tilde{q}'W$ and $q\tilde{q}\tilde{g}$ couplings are the same, while the $\tilde{q}\tilde{q}h$ coupling is proportional to $T_3 - Qs_W^2$, which is around $\frac{1}{3}$ for the up and $-\frac{5}{12}$ for the down sector. Therefore a cancellation of roughly one order of magnitude occurs. This cannot be broken by different squark masses, because the left-handed squarks form an $SU(2)$ doublet and again left-/right-handed squark mixing effects are tiny. For the subleading ZZ fusion channel and the electroweak corrections this argument does not hold. Here we indeed find corrections at a more natural level.

For supersymmetric pentagon diagrams there is an additional possibility with two colored particles exchanged, depicted in the upper-right corner of Fig. 1. Formally, the interference with the tree-level diagram is of order $\mathcal{O}(\alpha_s^2\alpha^2)$, which is as large as the Born contribution $\mathcal{O}(\alpha^3)$. However, these diagrams have completely different kinematic properties compared to the vector-boson-fusion topology. Combined with the large loop masses this leads to a negligible contribution.

From these arguments we see that there is not a single explanation for the smallness of the supersymmetric QCD corrections, but a set of mechanisms which can explain these at first sight surprising results.

On the right-hand side of Table 1 we show numerical results for all SPS parameter points, which probe typical different parts of the MSSM parameter space. As expected, the overall picture of our numerical results stays unchanged. We see that the supersymmetric QCD corrections are strongly suppressed and their electroweak counterpart is less or around one percent. A large mass splitting in the stop sector leads to comparably large effects for the SPS5 point.

4. Conclusions

We have presented a calculation of the next-to-leading order supersymmetric corrections to Higgs-boson production via vector-boson-fusion in the MSSM. This is an important ingredient for a precision analysis of the Standard-Model and the MSSM Higgs sector at the LHC. We find that the supersymmetric QCD corrections are reduced to a negligible level. This is due to various effects ranging from the color structure and the coupling structure to the kinematics of the process. The supersymmetric $\mathcal{O}(\alpha)$ contributions turn out to be at the percent level and therefore at a typical size for massive electroweak corrections. In general, the total corrections can reach up to four percent for parameter points still allowed by direct searches, with usual sizes at or below one percent, and typically negative sign.

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