Comparisons of Fixed Order Calculations and Parton Shower Monte Carlo for Higgs Boson Production in Vector Boson Fusion

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Abstract
A comparison of a fixed order prediction of the vector boson fusion Higgs boson production channel with the parton-shower Monte Carlo generator Herwig is shown. Herwig is found to be in good agreement with the leading order result, but differs significantly for differential distributions of the Higgs boson and jet kinematics at next-to-leading order. A reweighting method is described that improves the description of Herwig compared to the NLO result.

1. INTRODUCTION

An important search channel for the Higgs boson at the LHC is Vector boson fusion (VBF), which is included in the process $qq \to qqH$, where the Higgs boson is produced via the coupling to the gauge bosons. Feynman diagrams for this process at leading order are depicted in Fig. 1.

The experimental signature of the VBF process consists of two so-called tag-jets, which because the t- and u-channel diagrams are dominant, tend to be in the forward direction and in opposite detector hemispheres, the decay products of the Higgs boson in the central region and due to the absence of color flow only small additional hadronic activity in the central detector region. To accurately estimate cut efficiencies and acceptances higher order corrections are needed.

Higher order corrections for this process have been first evaluated in NLO QCD neglecting various interference terms and s-channel contributions [1, 2, 3, 4, 5], and subsequently including NLO QCD and NLO electroweak corrections in [6, 7], where all contributing diagrams, including s-channel diagrams have been taken into account. The electroweak corrections are about the same size as the strong corrections. The prediction of the total cross section has a scale uncertainty of only a few per cent.

However, for the simulation of the VBF process to evaluate experimental acceptances and cut efficiencies, a fixed order calculation is not sufficient, because it does not include a parton shower, hadronization, or an underlying event description. In experimental analyses rather parton-shower Monte Carlo generators (PS-MC) are used, which in general use a leading order matrix element[1]. It is thus difficult to make predictions of accepted cross sections after analysis cuts when one wants to make use of the precise higher order calculations. The accepted cross sections are necessary to evaluate the discovery potential at the LHC for the Higgs boson, and also, in case that no signal is observed, to place limits on the Higgs boson mass.

In addition to acceptance differences, the higher order calculations can also induce differences in the shapes of differential distributions that are used in experimental analyses. As long as no NLO PS-MC Monte Carlo generator is available, it is only possible to incorporate these by weighting the events of a PS-MC in a way that the kinematic distributions become as similar as possible to the NLO result.

In this note the acceptances of the PS-MC Herwig [9] and of the fixed order calculation in [6, 7] are compared. In addition, comparisons of differential distributions of kinematic variables are made and a possible reweighting method to improve the modeling of the PS-MC is proposed.

[1] Until very recently there was no PS-MC available combining an NLO matrix element with a parton-shower for VBF. Within NLO QCD such a matching has been presented recently in the POWHEG scheme in [8].

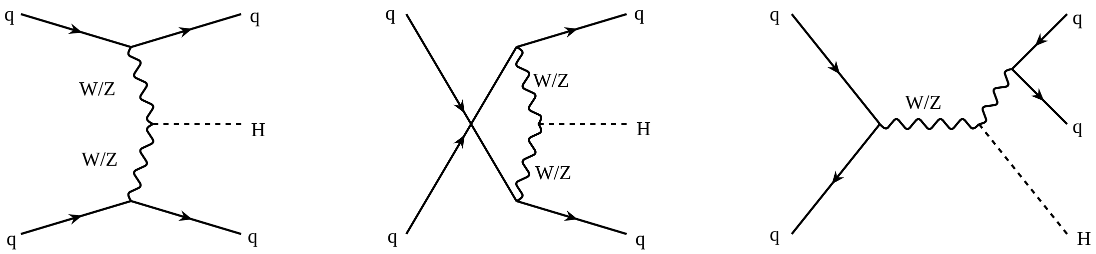

Fig. 1: Feynman diagrams for the process $qq \to qqH$ at leading order. Left: t-channel, middle: u-channel, right: s-channel.

2. SETUP

In the following comparisons are made for an assumed Higgs boson mass of $120\,\mathrm{GeV}$ and a LHC centre-of-mass energy of $14\,\mathrm{TeV}$.

The fixed order results shown in the following employ the program used in [6, 7] with the imput parameters $M_W = 80.425\,\mathrm{GeV}$, $\Gamma_W = 2.124\,\mathrm{GeV}$, $M_Z = 91.1876\,\mathrm{GeV}$, $\Gamma_Z = 2.4952\,\mathrm{GeV}$, $G_\mu = 1.16637 \times 10^{-5}\mathrm{GeV}^{-2}$, $m_t = 174.3\,\mathrm{GeV}$. All other input parameters are as in [6, 7]. The strong coupling constant is chosen as the same as in the used parton density function, where for the leading order result the CTEQ6L1 set [10] and for the NLO result the MRST2004qed set [11] set is used. Processes with external b-quark contributions are excluded. A renormalization and factorization scale of $\mu_R = \mu_F = M_W$ is used.

As PS-MC generator Herwig 6.510 [9] is used, using the same top quark mass as for the fixed order result. The Higgs boson is forced to decay into ZZ and both Z bosons are required to decay into neutrinos, in order not to introduce a sensitivity to the properties of the Higgs boson decay. The corresponding branching fractions are already removed from the cross sections quoted in the following for the Herwig PS-MC. The soft underlying event probability in Herwig was switched off.

Jets are reconstructed using a k_T-algorithm [12], as described in [13], with a resolution parameter of $D = 0.8$. For the fixed order result, all partons within $|y| < 5$, where y is the rapidity, are used as input for the jet algorithm. In the case of the PS-MC all stable particles after hadronization with $|y| < 5$ are taken into account.

Typical experimental VBF cuts as in [4] are used, requiring at least two jets with a transverse momentum of at least $20\,\mathrm{GeV}$ and $|y| < 4.5$. The two jets with the highest transverse momentum passing these requirements are taken as tag-jets. These two tag-jets are required to be in opposite detector hemispheres ($y_1 \cdot y_2 < 0$) and to have a separation in rapidity of at least 4 ($|y_1 - y_2| > 4$).

3. COMPARISONS

3.1 Accepted Cross Sections

Table 1 shows a comparison of the cross section with and without VBF cuts along with the cut efficiency for the fixed order calculation from [6, 7] and the Herwig parton shower generator. Compared to the full result from [6, 7], Herwig shows a too small cross section without cuts. When applying the VBF cuts, the cross section difference is much smaller. This is due to the fact that Herwig does not take s-channel contributions to the $qq \to qqH$ process into account. When comparing to the results from [6, 7] with the s-channel contributions excluded, the difference becomes much smaller.

It should be expected that when the s-channel contributions are not taken into account, the cross section by Herwig should agree with the LO prediction from [6, 7] using the CTEQ6L1 PDF set. However, this is not completely the case: Without cuts, Herwig predicts an about 4% smaller cross section than the program of [6, 7], and this difference increases to about 9% when VBF cuts are applied. The overall normalization difference can for example arise from different scale choices in the Herwig parton shower compared to the fixed order calculation. The selection efficiency of the VBF cuts is also slightly smaller in Herwig than in the LO prediction of the fixed order calculation. However, the selection efficiency is in good agreement to the NLO result of the fixed order calculation. This is due to the fact that by the use of a parton shower already parts of the higher order corrections are taken into account.

Since the selection efficiency in Herwig is the same as the one in the fixed order calculation, the Herwig cross section can be scaled to the one from the fixed order calculation to obtain a prediction of the accepted cross section.

program	order	PDF	$\sigma_{\text{no cuts}}[\text{fb}]$	$\sigma_{\text{VBF cuts}}[\text{fb}]$	$\epsilon_{\text{cuts}}[\%]$
fixed order	LO	CTEQ6L1	5406	1685	31.1
fixed order	NLO	MRST2004qed	5872	1665	28.3
fixed order, no s-channel	LO	CTEQ6L1	4216	1685	40.0
fixed order, no s-channel	NLO	MRST2004qed	4290	1656	38.5
Herwig	LO+PS	CTEQ6L1	4054	1547	38.2

Table 1: Cross sections with and without VBF cuts and cut efficiencies.

3.2 Differential Distributions

In addition to the total cross section also the shape of differential distributions is in general changed by higher order corrections. In addition to the observables used in the VBF cuts, this is also important for experimental analysis for two reasons:

- The VBF cuts are rather soft, especially the cut of $20\,\text{GeV}$ on the transverse momentum of the tagging jet. In general, additional kinematic variables like the invariant mass of the two tag-jets or the difference of their azimuthal angles is used in experimental analyses to extract the signal from the background. A good modeling of these variables is thus desirable.
- Recently there has been some interest in analyses that use highly boosted Higgs bosons with a very high transverse momentum to discover the Higgs boson also in its decay into bottom quarks [14, 15]. While currently no such analysis exists for the VBF production channel, it might be of interest in the future. For such an analysis the accurate prediction of the transverse momentum of the produced Higgs boson is very important.

To assess the influence of higher order corrections on the shape of differential distributions and to compare the prediction of the Herwig PS-MC generator to the fixed order calculation, the following procedure has been applied: First, the VBF cuts as described in the previous section were applied. To compare Herwig to the LO prediction, it was decided to normalize the event sample to the LO cross section after cuts, thus removing the 9% discrepancy that was observed.

The results of this comparison are shown in Figure 2, where the transverse momenta and rapidities of the Higgs bosons and the tag-jets, the invariant mass of the tag-jets and the difference of their azimuthal angle is plotted. In the lower part of the sub-figures, the ratio of the fixed order calculation to Herwig is shown.

The shapes of the Herwig PS-MC prediction are very close to the LO prediction, as should be expected, as Herwig uses a LO matrix element. The parton shower does not seem to influence the shapes of the distributions significantly. The biggest difference can be seen in the invariant dijet mass of the tag-jets, but overall the agreement is within 10%.

Compared to the NLO prediction, Herwig predicts a significantly harder transverse momentum spectrum both for the Higgs boson and for the tag-jets[2]. Also the invariant dijet mass is preferred to be slightly larger in Herwig.

[2]Of course the transverse momenta of the Higgs boson and the tag-jets are correlated.

3.3 Reweighting of PS-MC

To partially account for the differences in the transverse momentum spectra, a simple reweighting method has been applied, where the Herwig events are weighted using the ratio to the NLO prediction in only one variable. This observable has been chosen to be the transverse momentum of the Higgs boson, since the differences are largest in this variable. The weights assigned to the Herwig events are chosen according to:

$$w = \frac{\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^{\mathrm{H}}}(\text{NLO, MRST2004qed})}{\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^{\mathrm{H}}}(\text{Herwig, CTEQ6L1})} \tag{1}$$

The dashed Histogram in the lower part Figure 2 (a), which is the ratio between the NLO prediction from [6, 7] and the Herwig prediction after VBF cuts, was fitted with a 3rd order polynomial in p_T^H to be used as a reweighting function for the Herwig events. In principle also the LO prediction could be taken from [6, 7], but the shape of the transverse momentum distribution of the Higgs boson is identical to the one from Herwig in this case.

Figure 3 shows the comparison of the differential distributions after the reweighting procedure. By construction, the Herwig prediction for the transverse momentum of the Higgs boson now fits exactly the one of the NLO prediction. But due to the kinematic correlations, also an improved description of the tag-jet transverse momenta and to a lesser extent the invariant dijet mass is obtained. The reweighted Herwig prediction is almost everywhere within 10% of the NLO prediction.

CONCLUSIONS

Acceptances and differential cross sections in the VBF process have been shown to agree between Herwig and the fixed order result from [6, 7] in LO. The differences between the NLO predictions and the LO result in differential cross sections can be partially taken into account by a reweighting of Herwig events using a weight that depends on the transverse momentum of the generated Higgs boson. In this way an improved description can be obtained, though it would be better to have a fully merged NLO PS-MC available. It should be noted that in the VBF process, the electroweak NLO corrections have comparable influence to the QCD corrections on the cross section and on the shape of differential distributions [6, 7], thus a NLO PS-MC would have to take the electroweak corrections also into account to give the best available description of the VBF process.

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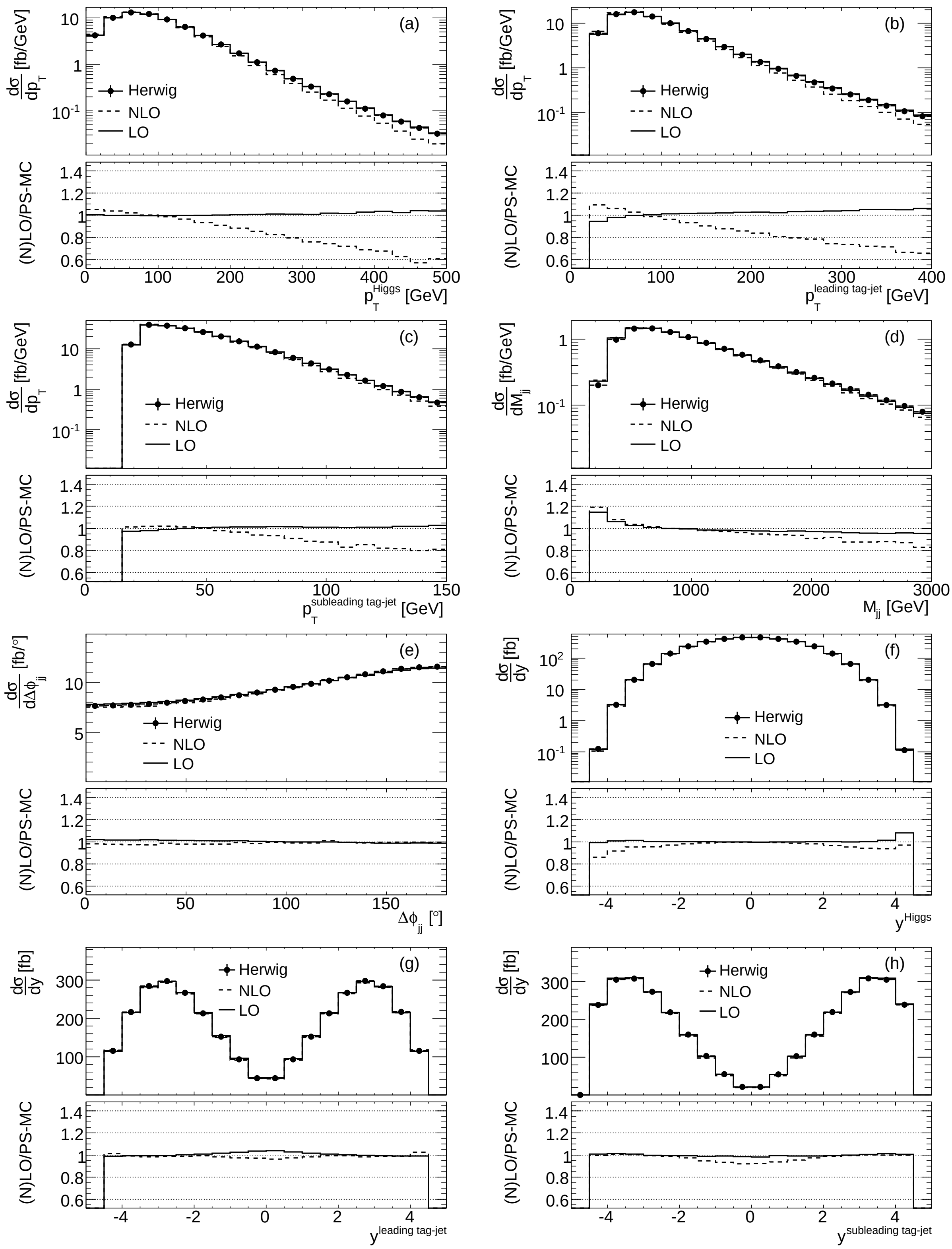

Fig. 2: Differential distributions after VBF cuts, before the reweighting procedure described in the text.

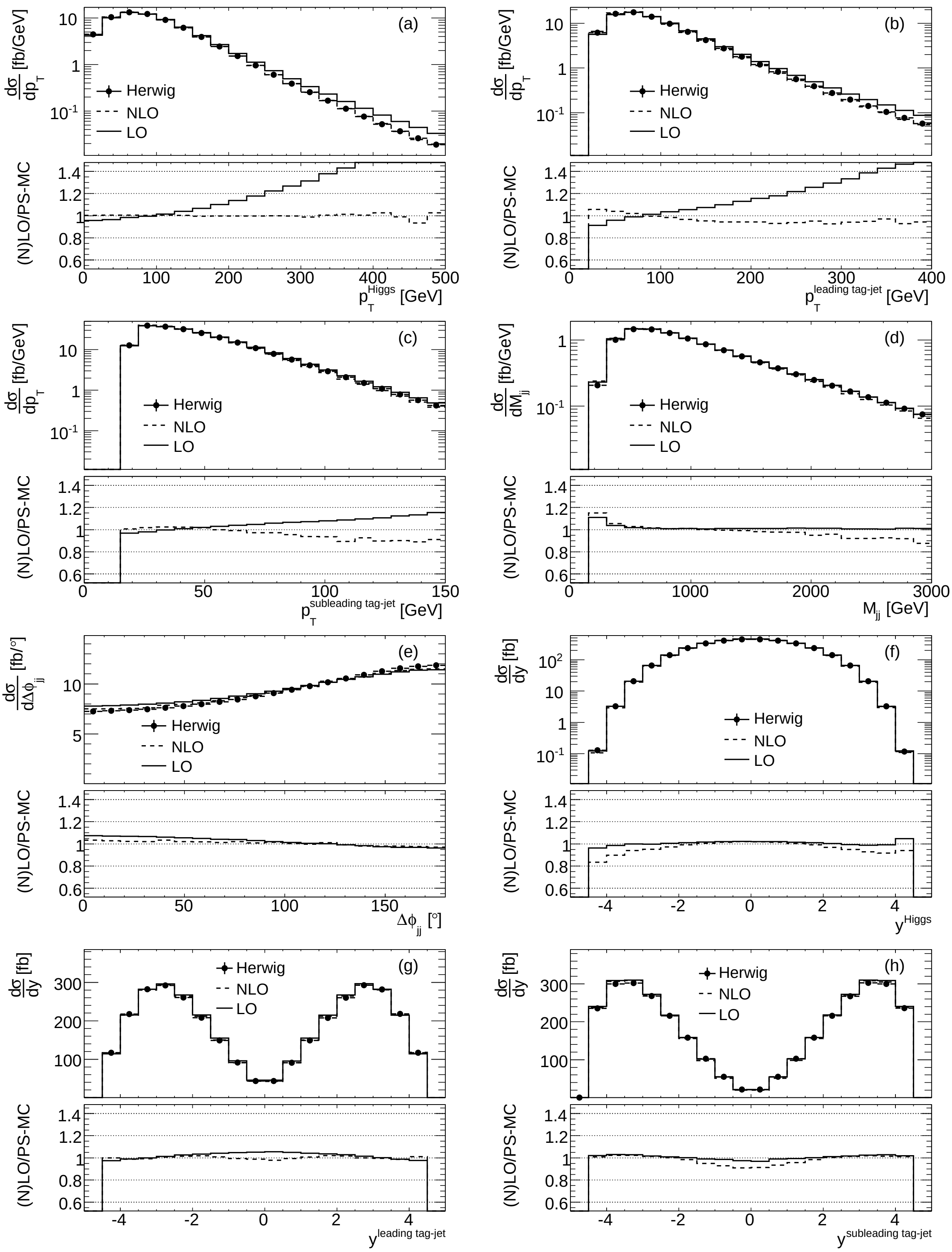

Fig. 3: Differential distributions in after VBF cuts, including the reweighting procedure described in the text.