Physics Letters B 781 (2018) 672–677

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Second-order QCD effects in Higgs boson production through vector boson fusion

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ARTICLE INFO

Article history:
Received 8 February 2018
Accepted 23 April 2018
Available online 26 April 2018
Editor: G.F. Giudice

Keywords:
QCD
Jets
Collider physics
NLO and NNLO calculations

ABSTRACT

We compute the factorising second-order QCD corrections to the electroweak production of a Higgs boson through vector boson fusion. Our calculation is fully differential in the kinematics of the Higgs boson and of the final state jets, and uses the antenna subtraction method to handle infrared singular configurations in the different parton-level contributions. Our results allow us to reassess the impact of the next-to-leading order (NLO) QCD corrections to electroweak Higgs-plus-three-jet production and of the next-to-next-to-leading order (NNLO) QCD corrections to electroweak Higgs-plus-two-jet production. The NNLO corrections are found to be limited in magnitude to around ±5% and are uniform in several of the kinematical variables, displaying a kinematical dependence only in the transverse momenta and rapidity separation of the two tagging jets.

1. Introduction

The discovery of the Higgs boson at the CERN Large Hadron Collider (LHC) [1] has initiated an intensive program of precision measurements of the Higgs boson properties, and of its interactions with all other elementary particles. A large spectrum of Higgs boson decay modes and production channels are being investigated at the LHC. The Higgs boson can be produced at hadron colliders [2] either through its Yukawa coupling to the top quark (in gluon fusion through a closed top quark loop or by associated production with top quarks) or through its coupling to the electroweak gauge bosons. This electroweak coupling gives rise to two production modes: associated production with a vector boson, and vector boson fusion (VBF).

At LHC energies, the VBF process is the second-largest inclusive production mode for Higgs bosons, amounting to about 10% of the dominant gluon fusion process. The detailed experimental study of the VBF production mode probes the electroweak coupling structure of the Higgs boson, thereby testing the Higgs mechanism of electroweak symmetry breaking. These studies do however require that VBF events can be discriminated against other Higgs boson production modes, especially against gluon fusion. This can be accomplished by exploiting the fact that at leading-order (LO) VBF production proceeds with an initial state configuration of two quarks/anti-quarks each radiating a weak vector boson, which then fuse to form the observed Higgs boson. The incoming quarks are deflected and lead to energetic jets at large rapidities. The distinctive VBF signature is therefore given by Higgs-plus-two-jet production, with the jets being strongly separated in rapidity, and forming a di-jet system of high invariant mass. These requirements can be formulated in a set of VBF cuts [3,4] ensuring an event selection that enhances VBF events while suppressing the other production modes.

Perturbative corrections to Higgs boson production via VBF (electroweak Higgs-plus-two-jet production) have been derived at next-to-leading order (NLO) in QCD [5–8] and in the electroweak theory [9]. To optimise the VBF event selection cuts, one would also like to have a reliable description of extra jet activity in the VBF process. To this end, NLO QCD corrections have also been obtained for electroweak Higgs-plus-three-jet production [10–12]. Next-to-next-to-leading order (NNLO) QCD corrections to the inclusive VBF Higgs production cross section were found to be very small [13], they are further improved by third-order (N3LO) corrections [14]. However, more sizable NNLO QCD effects were observed for fiducial cross sections and differential distributions in the VBF Higgs-plus-two-jet production process [15]. The latter cal-

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https://doi.org/10.1016/j.physletb.2018.04.046
0370-2693/

culation used the NLO QCD Higgs-plus-three-jet production results of Ref. [10] as an input, employing a projection to Born-level kinematics to construct the NNLO differential cross section.

In this paper, we present an independent derivation of the second-order QCD corrections to the electroweak Higgs-plus-two-jet (VBF-2j) production process, and use these to make NLO QCD predictions for VBF Higgs-plus-three-jet production (VBF-3j) and NNLO QCD predictions for VBF-2j production. Both predictions are fully differential in the final state kinematics, and allow the computation of fiducial cross sections and differential distributions. In Section 2, we describe the calculational method and its implementation in the NNLOJET framework. Section 3 contains numerical results for the cross sections and distributions in the VBF-3j and VBF-2j processes at LHC, and Section 4 concludes with an outlook.

2. Method

The Born-level VBF process consists of two independent quark lines, each emitting an electroweak gauge boson, linked through a HWW or HZZ vertex, as depicted in Fig. 1. The lack of colour exchange between the two initial state partons means hadronic activity in the central region is suppressed with respect to other important Higgs production channels, where the complicated colour structure means that radiation in the central region is enhanced. Precisely this feature lies at the heart of the VBF cuts designed to single out VBF over other production modes [3,4]. Besides enhancing the relative contribution of VBF processes, the VBF cuts also strongly suppress interference effects between both quark lines, which are present for identical quark flavours.

When computing higher order QCD corrections, one can exploit this Born-level factorisation of the VBF process into two independent quark lines. Due to colour conservation, a single gluon exchange is forbidden between the quark lines, such that NLO corrections can be computed by considering corrections to the each quark line independently. Since each single quark line in the VBF process is identical to the deeply inelastic scattering (DIS) process of a quark on a vector boson current, this factorisation into two independent processes is also called the "structure function approach" [16]. Beyond NLO, one can define the structure function approach by forbidding colour exchange between the quark lines. This results in a gauge-invariant subset of diagrams. Several studies have been performed, showing that the contributions that are neglected in the structure function approach are very small in the relevant phase-space regions defined by VBF cuts, even if they are sizeable when no cuts are used [9,12,17]. Interference effects between the VBF production channel and other production channels are also negligible [18].

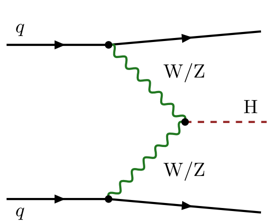

Fig. 1. Born-level vector boson fusion process.

Second order QCD corrections constitute of contributions from double real radiation (RR), single real radiation at one loop (RV) and two-loop virtual (VV), see Fig. 2. Working in the structure function approach, the corrections to the basic VBF process can be distributed amongst the quark lines, e.g. a real emission off one quark line and a virtual correction to the other line (as in Fig. 2) contributes to the RV process.

In our calculation, we implemented the matrix elements for all relevant parton-level subprocess, and used the antenna subtraction technique [19] to construct subtraction terms for the infrared real radiation singularities in the RR and RV contributions so that these contributions are finite over the whole of phase space. The implicit singularities in the subtraction terms are then rendered explicit through integration over the unresolved phase space and then combined with the VV contribution to render this contribution also finite and amenable to numerical integration in four space–time dimensions. The numerical implementation is performed in the NNLOJET parton-level event generator framework, which provides the phase-space generator, event handling and analysis routines as well as all unintegrated and integrated antenna functions [20] that are used to construct the subtraction terms.

3. Results

For our numerical computations, we use the NNPDF3.0 parton distribution functions [21] with the value of $\alpha_s(M_Z) = 0.118$ at NNLO, and $M_H = 125$ GeV, which is compatible with the combined results of ATLAS and CMS [22]. Furthermore, we use the following electroweak parameters as input:

$$M_W = 80.398 \text{ GeV}, \qquad \Gamma_W = 2.141 \text{ GeV},$$
$$M_Z = 91.188 \text{ GeV}, \qquad \Gamma_Z = 2.495 \text{ GeV}. \tag{3.1}$$

Jets are reconstructed using the anti-k_T algorithm [23] with a radius parameter $R = 0.4$, and are ordered in transverse momentum. The renormalisation and factorisation scales are chosen as suggested in [15]:

$$\mu_0^2(p_T^H) = \frac{M_H}{2}\sqrt{\left(\frac{M_H}{2}\right)^2 + \left(p_T^H\right)^2}. \tag{3.2}$$

In all plots, the uncertainty bands denote the scale uncertainty taking $\mu_R = \mu_F = \{\frac{1}{2}, 1, 2\} \times \mu_0$ whereas the error bars in ratios correspond to the statistical uncertainty of the numerical Monte Carlo integration.

As a validation of our calculation, we compare against the fully inclusive cross section [13,15] finding very good agreement as shown in Table 1. We would like to point out the substantial technical difference between our calculation and the approach used

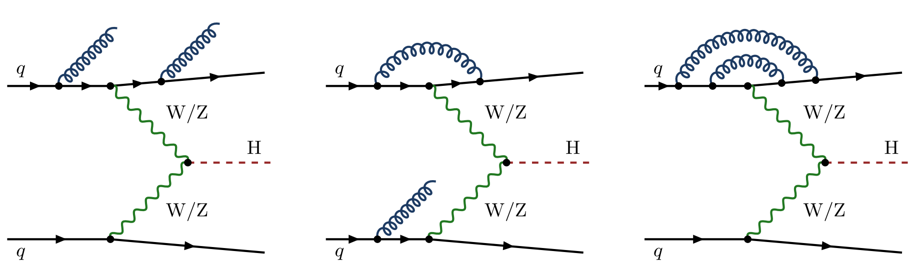

Fig. 2. Examples of second order QCD corrections (RR, RV, VV) to the VBF process.