Vector Boson Pair Production via Vector Boson Fusion at NLO QCD

Giuseppe Bozzi¹, Barbara Jäger², Carlo Oleari³ and Dieter Zeppenfeld¹
¹ Institut für Theoretische Physik, Universität Karlsruhe, P.O.Box 6980, 76128 Karlsruhe, Germany
² KEK Theory Division, Tsukuba 305-0801, Japan
³ Università di Milano Bicocca and INFN Sezione di Milano Bicocca, 20126 Milano, Italy
E-mail: giuseppe@particle.uni-karlsruhe.de

Abstract. NLO QCD corrections to Vector Boson Pair Production via Vector Boson Fusion have recently been calculated and implemented in a parton-level Monte-Carlo program with full experimental cuts. We briefly sketch the elements of the calculation and show numerical results for the Large Hadron Collider.

1. Introduction
The Vector Boson Fusion (VBF) process $qq \rightarrow qqH$ is one of the most promising channels for the discovery of the Higgs particle and the measurement of its properties at the Large Hadron Collider (LHC) [1]. It proceeds through a $t$–channel scattering of the two initial-state quarks mediated by a weak boson, with the Higgs emitted off the boson propagator. The kinematic features that make this process phenomenologically relevant are: the presence of two highly-energetic jets in the final state, the large rapidity interval between these jets and the absence of noticeable jet activity inside this rapidity interval. Moreover the Next-to-Leading Order (NLO) QCD corrections to the total cross sections [2] and for the differential distributions [3] have been found to be quite modest (5-10% higher than Leading Order (LO)), thus pointing towards a good stability of the perturbative result. Even though the cross section for the VBF process is somewhat smaller than the one for the gluon fusion $gg \rightarrow H$ channel at the LHC, the distinctive features cited above greatly help in distinguishing the signal from the backgrounds and make VBF an ideal candidate for Higgs discovery and precision measurements.

One of the most relevant backgrounds to a VBF $H \rightarrow VV$ signal is the process $qq \rightarrow qqVV$, i.e. vector boson pair production via VBF [4]. It shows exactly the same kinematical features as VBF Higgs production, thus being an irreducible background. In addition, it is known that the scattering of longitudinal vector bosons is intimately related to the mechanism of electroweak symmetry breaking (EWSB), and an enhancement of $qq \rightarrow qqVV$ over the Standard Model predictions at high center-of-mass energies could be a possible signal of strong EWSB (see, for instance, [5] and references therein).

It is thus clear that an accurate prediction for the electroweak production of a vector boson pair plus two jets is mandatory for new physics searches at the LHC. In the following we will present the results obtained in three recent papers where we computed the NLO QCD corrections.
to the processes $qq \rightarrow qqW^+W^-$ [6], $qq \rightarrow qqZZ$ [7], $qq \rightarrow qqW^\pm Z$ [8], including the full leptonic decays of the vector bosons. The calculations have been implemented in a fully-flexible parton level Monte-Carlo program, allowing for the computation of jet observables and a straightforward implementation of experimental cuts.

2. Selected topics from the calculation

The main challenges of the calculation were the huge number of Feynman diagrams involved and the numerical instabilities arising from pentagon contributions to the virtual part of the cross section.

When computing a multi-parton process (in this case, a $2\rightarrow 6$ process considering full leptonic decays of the vector bosons) one has to find an efficient way to speed up the numerical evaluation. In our Monte-Carlo code the sum of sub-amplitudes encountered in several diagrams, and involving only EW bosons and leptons, is computed only once per phase-space point (for details, see [6]): this method is particularly efficient in the computation of real emission corrections, due to the large number of contributing diagrams.

The soft and collinear singularities of the NLO real contributions have been taken into account by means of the standard Catani-Seymour dipole subtraction [9]. Since the divergences only depend on the colour structure of the external partons, the subtraction terms are identical in form to the ones appearing in Higgs production via VBF [3].

The EW bosons exchanged in the $t$-channel are colour-singlets, thus there cannot be any virtual contribution at $O(\alpha_S)$ from gluons attached both to the upper and lower quark lines. This allows us to consider virtual radiative corrections separately for the single quark lines, leading to diagrams containing loops with up to five external legs (pentagons). After the cancellation of the infrared poles between real and virtual contributions, the finite remainder can be computed by means of the Passarino-Veltman reduction formalism [10] in the case of two-, three- and four-point tensor integrals. In the case of pentagons, numerical instabilities show up when kinematical invariants, such as the Gram determinant, become small for some region of phase space. We have thus used for the pentagons the recently proposed Dennar-Dittmaier alternative reduction formalism [11], bringing down the numerically unstable fraction of events to a per-mille level (for details, see [8]).

3. Numerical results

In the following we will present numerical results at NLO QCD accuracy obtained with our Monte-Carlo code for EW $WWjj$, $ZZjj$, $WZjj$ production at the LHC.

We used the CTEQ6M parton distributions with $\alpha_S=0.118$ at NLO and the CTEQ6L1 set at LO [12]. We chose $m_Z=91.188$ GeV, $m_W=80.419$ GeV and $G_F=1.166\times10^{-5}$ as EW input parameters, obtaining $\alpha_{QED}=1/132.54$ and $\sin^2\theta_W=0.22217$. We have set fermion masses to zero, neglecting external bottom and top quark contributions. Jets have been reconstructed by means of the $k_T$-algorithm [13, 14] with resolution parameter $D=0.8$.

Typical VBF cuts have been imposed: here we show those used in the $W^\pm Z$ case.

- Two hard ”tagging” jets: $p_Tj \geq 20$ GeV, $|y_j| \leq 4.5$, $M_{jj} > 600$ GeV
- Large rapidity separation between jets: $\Delta y_{jj} > 4$, $y_j1 \times y_j2 < 0$
- Lepton cuts: $p_Tl \geq 20$ GeV, $|\eta_l| \leq 2.5$, $m_{ll} \geq 15$ GeV
- ”Separation” cuts: $\Delta R_{jl} \geq 0.4$, $\Delta R_{ll} \geq 0.2$

where $\Delta R_{jl}$ and $\Delta R_{ll}$ denote the jet-lepton and lepton-lepton separation in the rapidity-azimuthal angle plane respectively, and $m_{ll}$ the invariant mass of an electron or muon pair.

In Figure 1 (from [8]) we show the total cross section displayed as a function of the factorization and renormalization scales $\mu_{F,R} = \xi_{F,R}\mu_0$ in the case of $W^\pm Z$ production. We
have considered two possible values for the central scale: $\mu_0 = (m_Z + m_W)/2$ or $\mu_0 = Q$, where $Q$ is the momentum transfer carried by the exchanged vector boson in VBF graphs (for details, see [8]). The K-factor is $K=0.97$ in the first case and $K=1.04$ in the second one. In both cases we can see that the scale dependence, for instance in the range $0.5 < \xi < 2$, is greatly reduced when passing from LO (nearly 10%, dotted black curves) to NLO (nearly 2%), where we have three cases: $\xi_F = \xi_R = \xi$ (solid red lines), $\xi_F = 1, \xi_R = \xi$ (dashed green lines), $\xi_F = \xi, \xi_R = 1$ (dot-dashed blue lines).

In Figure 2 (from [6]) we present the transverse-momentum distribution of the tagging jet with the highest $p_T$ in WW production via VBF (left), with the corresponding K-factor (right).

Finally, in Figure 3 (from [7]) we show the differential distribution for EW Z pair production with respect to the invariant mass $M_{ZZ}$ without (left) and with (right) the inclusion of the
Figure 3. Distribution of the invariant mass $M_{ZZ}$ in ZZ production via VBF without (left) and with (right) the Higgs boson contribution.

Higgs contribution and for a scale $\mu = Q$. Apart from the pronounced resonance behaviour visible in the right plot, we note that the LO and NLO are virtually indistinguishable in both cases, indicating an excellent stability of the perturbative calculation for this scale choice.

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