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PROCEEDINGS OF SCIENCE

Beyond the t-channel Approximation: Next-to-Leading Order QCD Corrections to Electroweak Higgs Boson Plus Three Jet Production at the LHC

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In this talk we discuss the implementation of the full next-to-leading order QCD corrections to electroweak Higgs boson plus three jet production at the LHC within the `Matchbox` framework of the `Herwig++` event generator. We also present numerical results for integrated cross sections and kinematic distributions.

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1. Introduction

The existence of a new boson with a mass in the range of 125–126 GeV, with a spin most likely equal to zero and with even parity has been confirmed with increasing confidence in recent reports by the ATLAS and CMS Collaborations [1, 2, 3, 4]. Furthermore, the new particle exhibits production and decay rates similar to a Standard Model (SM) Higgs boson [5, 6, 7, 8, 9, 10].

Higgs boson production via vector boson fusion (VBF), i.e., the t-channel $\mathcal{O}(\alpha_{QED}^3)$ merging of two weak bosons in the reaction $qq \to qqH$, is an essential channel at the LHC for constraining Higgs boson couplings to gauge bosons and fermions. In the current experimental data from the LHC, the ATLAS Collaboration finds 3σ evidence [9] for Higgs boson production via VBF and the CMS Collaboration finds 1.3σ evidence [11].

For this process the observation of two forward tagging jets is crucial for the reduction of background. Requiring, in addition, that there is no extra radiation within the rapidity gap between the forward tagging jets [12, 13, 14], i.e., imposing a central jet veto (CJV), suppresses standard QCD backgrounds, as well as Higgs production via gluon-gluon fusion in association with two jets (GF Hjj) [12, 13, 14].

To exploit the CJV strategy for Higgs boson coupling measurements, it is therefore necessary to know the reduction due to the CJV accurately. Thus it is of interest to calculate the ratio of Higgs boson plus three jet (EW $Hjjj$) production (where the third jet is required to be between the two tagging jets) to the inclusive Higgs boson plus two jet (EW Hjj) cross section.

Recently the competing GF $Hjjj$ has been computed within the heavy top effective theory approximation to next-to-leading order (NLO) in perturbative QCD [15]. The heavy top effective theory approximation for $Hjj(j)$ has been validated against $Hjj(j)$ amplitudes where the top mass dependence has been kept in Refs. [16, 17].

Approximated results at NLO QCD for EW VBF $Hjjj$ production were presented sometime ago in [18, 19]. There, the t-channel approximation was used and additionally, the inclusion of pentagon and hexagon one-loop Feynman diagram topologies (Figure 1, last two diagrams) and the corresponding real emission contributions were omitted and estimated to contribute at the per-mille level. Recently, parton-shower effects on EW VBF $Hjjj$ were investigated in Ref. [20] within the t-channel approximation[1]. In view of the relevance to the determination of Higgs boson couplings, we will present results from [22, 23], where those approximations are lifted, and the full NLO QCD corrections to the $\mathcal{O}(\alpha_s \alpha_{EW}^3)$ production of a Higgs boson in association of three jets is calculated for the first time. In this proceedings, we show results for the inclusive sample and leave for future work a thorough comparison with the VBF approximation.

The remainder of this proceedings is organized as follows: Details of the NLO calculation are presented in Section 2. Numerical results and conclusions are shown in Section 3 and in Section 4, respectively.

2. Calculational Details

For the leading order (LO) $2 \to H + n$ ($n = 2, 3, 4$) parton matrix elements, we employ the built–in spinor helicity library of the `Matchbox` module in the `Herwig++` event generator [24, 25] to

[1] Parton-shower effects were investigated also in Ref. [21].

construct the full amplitude from hadronic currents [26]. The LO $2 \to H+n$ ($n = 2,3,4$) parton matrix elements were also cross checked against `Sherpa` [27, 28], `VBFNLO` [29, 30, 31], and `Hawk` [32, 33]. The Catani–Seymour dipole subtraction terms [34] are generated automatically by the `Matchbox` module [26], and for efficient generation of phase space points, we utilize a diagram-based multichannel phase space sampler [26].

The computation of the interference of the virtual one–loop amplitude with Born amplitudes, is calculated with the aid of the helicity amplitude technique described in Ref. [35], using the program described in Ref. [36], which also provides an independent version of the Born amplitudes, providing a valuable internal consistency check of our implementation. A representative set of one–loop Feynman diagram topologies that contribute to the virtual corrections are depicted in Figure 1. To evaluate the one–loop tensor coefficients, we use the Passarino-Veltman approach [37] up to four-point functions, and the Denner-Dittmaier scheme [38], following the layout and notation of [36], to numerically evaluate the five and six point coefficients. The one–loop scalar integrals are in turn evaluated using the program `OneLOop` [39]. Complex masses and finite width effects in gauge boson propagators are calculated in the complex mass scheme [40, 41]. The resulting one–loop amplitudes for specific phase space points have been cross checked against `GoSam` [42].

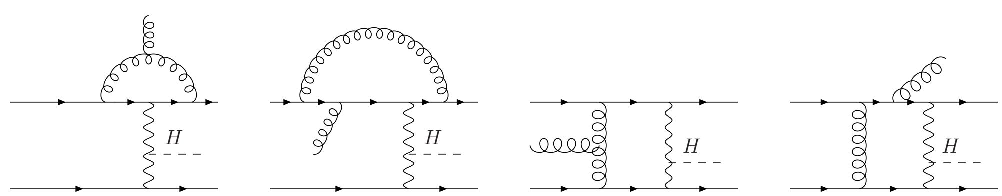

Figure 1: A representative selection of one-loop Feynman diagram topologies for EW $Hjjj$ production.

The numerical stability of our code, is tested by employing a Ward identity check at each phase space point and each Feynman diagram [36] – at the cost of a small increase in computing time. Upon failure of the Ward identity check, the amplitudes of the gauge related topology are set to zero. The failure rate is at the per-mille level and hence under control. This method has also been successfully applied in other scattering processes with $2 \to 4$ kinematics [43, 44], however, in the work presented here, the method is applied to a process which involves loop propagators with complex masses for the first time.

The color structure associated with the computation of color correlated Born matrix elements has been performed by `ColorFull` [45] and cross checked against `ColorMath` [46]. As a further check of our framework, we have implemented the corresponding calculation of electroweak Hjj production and, subsequently, performed cross checks against `Hawk` [32, 33] and VBFNLO [29, 30, 31].

We refer to our implementation of the NLO corrections in perturbative QCD for electroweak Higgs boson plus two and three jet production in the `Matchbox` framework as `HJets++`.

3. Results

In this section, we present results for a LHC of center-of-mass energy $\sqrt{s} = 14$ TeV. Here, we do not include parton shower and harmonization effects in our simulations. Instead the matrix

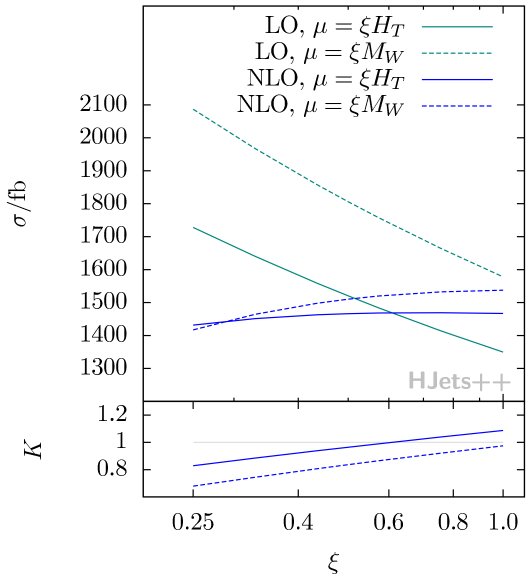

Figure 2: The $Hjjj$ inclusive total cross section (in fb) at LO (cyan) and at NLO (blue) for the scale choices, $\mu = \xi M_W$ (dashed) and $\mu = \xi H_T$ (solid). The lower panel displays the K-factor, $K = \sigma_{NLO}/\sigma_{LO}$ f or $\mu = \xi M_W$ (dashed) and $\mu = \xi H_T$ (solid).

element partons are recombined into jets according to the anti-k_T algorithm [47] using `FastJet` [48] with $D = 0.4$ and E-scheme recombination. We select events with at least three jets having transverse momentum $p_{T,j} \geq 20$ GeV and rapidity $|y_j| \leq 4.5$ and order the jets according to their transverse momentum.

We use the CT10 [49] parton distribution functions with $\alpha_s(M_Z) = 0.118$ at NLO, and the CTEQ6L1 set [50] with $\alpha_s(M_Z) = 0.130$ at LO. We use the five-flavor scheme for the running of α_s. We choose $m_Z = 91.188\,\text{GeV}$, $m_W = 80.419002\,\text{GeV}$, $m_H = 125\,\text{GeV}$ and $G_F = 1.16637 \times 10^{-5}\,\text{GeV}^{-2}$ as electroweak input parameters and derive the weak mixing angle $\sin\theta_W$ and α_{QED} from SM tree level relations. All fermion masses (except the top quark) are set to zero and the CKM matrix is taken to be diagonal. Widths are fixed to the following values: $\Gamma_W = 2.0476$ GeV and $\Gamma_Z = 2.4414$ GeV.

In Figure 2, we show the LO and NLO total cross-sections for inclusive cuts for different values of the factorization scale (μ_F) and renormalization scale (μ_R), varied around the central scale, μ for two different scale choices, $M_W/2$, and the scalar sum of the jet transverse momenta, $H_T/2$ with $H_T = \sum_j p_{T,j}$. In general, we find – as expected – a decreased scale dependence in the NLO results. We also note that the central values for the various scale choices are closer to each other at NLO. The uncertainties, obtained by varying the central value a factor two up and down, are around 25% (28%) at LO and 2% (8%) at NLO using $H_T/2$ ($M_W/2$) as scale choice. For the scale choice $\mu = H_T/2$, we obtained $\sigma_{LO} = 1520(8)^{+208}_{-171}$ fb and $\sigma_{NLO} = 1466(17)^{+1}_{-35}$ fb. Studying differential distributions, we find that these generally vary less using the scalar transverse momentum sum choice, used from now on.

On the left-hand side of Figure 3, the differential distribution of the third jet, (i.e., the jet which would be vetoed in a CJV analysis), is shown. Here we find large K factors in the high

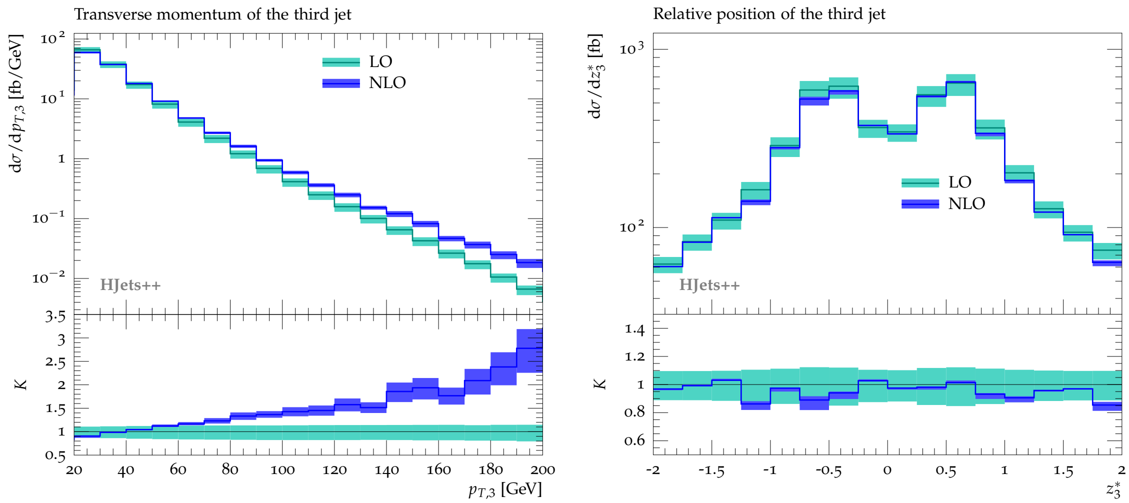

Figure 3: Differential cross section and K factor for the p_T of the third hardest jet (left) and the normalized centralized rapidity distribution of the third jet w.r.t. the tagging jets (right). Cuts are described in the text. The bands correspond to varying $\mu_F = \mu_R$ by factors 1/2 and 2 around the central value $H_T/2$.

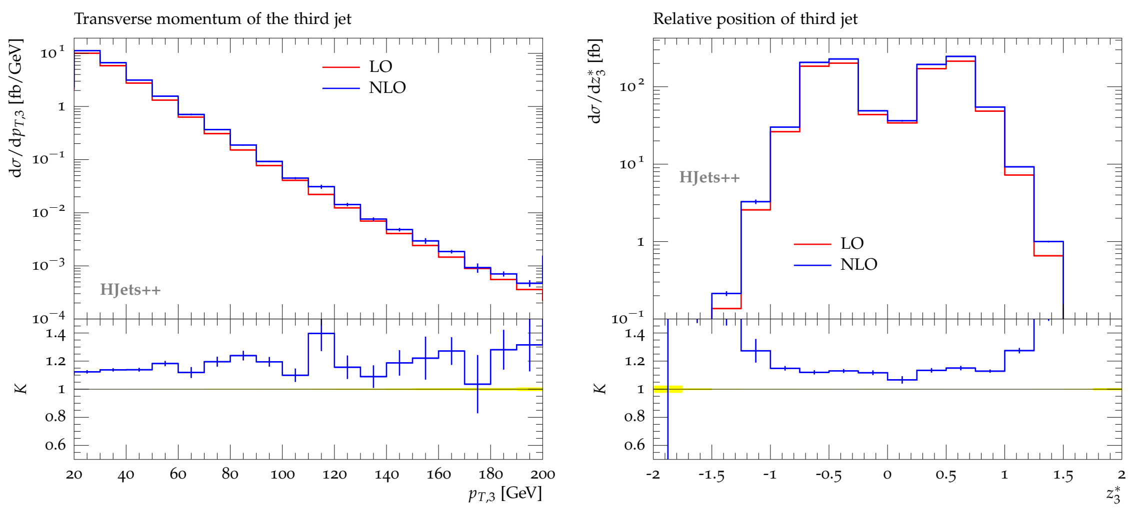

Figure 4: Differential cross section and K factor for the p_T of the third hardest jet (left) and the normalized centralized rapidity distribution of the third jet w.r.t. the tagging jets (right) with $\mu_R = \mu_F = H_T$. Beyond the inclusive cuts described in the text, we include the set of VBF cuts: $m_{12} = \sqrt{(p_1+p_2)^2} > 600$ GeV and $|\Delta y_{12}| = |y_1 - y_2| > 4.0$.

energy tail of the transverse momentum distribution. However, when VBF cuts [2] are imposed the K factor is almost flat as a function of the transverse momentum of the third jet (see the left-hand side of Figure 4). On the right-hand side of Figure 3, we show the normalized centralized rapidity distribution of the third jet w.r.t. the tagging jets, $z_3^* = (y_3 - \frac{1}{2}(y_1+y_2))/(y_1-y_2)$. This variable, showing how the third jet tends to accompany one of the leading jets appearing at $1/2$ and $-1/2$ respectively, beautifully displays the VBF nature present in the process.

[2] For the VBF cuts we have chosen to include the following cuts in addition to the inclusive cuts described in the main text : $m_{12} = \sqrt{(p_1+p_2)^2} > 600$ GeV and $|\Delta y_{12}| = |y_1 - y_2| > 4.0$

This effect is even more pronounced when VBF cuts are applied (see Figure 4), and should be contrasted with the gluon fusion production mechanism where QCD radiation in the rapidity gap region between the leading two jets is much more common [51, 52, 16, 15].

4. Conclusions

In this proceedings, we have presented complete results at NLO QCD for electroweak Higgs boson production in association with three jets. We have found that the NLO corrections to the total inclusive cross section are moderate for inclusive cuts using the scale choice of $H_T/2$. However, for the scale choice of $M_W/2$, the NLO corrections can be more significant. The scale uncertainty decreases from around 25%(28%) at LO down to about 2%(8%) at NLO using the scale choice of $H_T/2$ ($M_W/2$). We have also presented numerical results showing the impact of VBF selection cuts on the transverse momentum of the third jet, $p_{T,3}$, and its relative position w.r.t. the two leading jets, z_3^*.

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