Analyzing Higgsstrahlung with WHIZARD

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Abstract

We analyzed the process $e^+e^- \to HZ$, also called Higgsstrahlung, with a hadronic Z decay using the Monte Carlo Event Generator WHIZARD. The cross section of the process as well as the differential distributions of the transverse momentum of the jets, the decay products of the Z-bosons, were determined at both leading order and next-to-leading order in Quantum Chromodynamics. The results were compared to results that were obtained using MadGraph. While MadGraph and WHIZARD are in good agreement at leading order there are differences at next-to-leading order. However, due to unphysical behavior of the distributions that were obtained with MadGraph, it is concluded that the WHIZARD results can still be assumed to be correct, both at leading order and next-to-leading-order.

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1 Introduction

The collider currently driving High Energy Physics is the Large Hadron Collider at CERN. As the name says it collides hadrons, namely protons. Compared to a lepton collider this has the advantage that much larger center of mass energies can be reached. However, the downside is that the precision of measurements at a hadron collider does not reach the precision of a lepton collider, due to the fact that a hadron is not an elementary particle, which leads to a larger background.
At the Large Hadron Collider much progress has been made including the discovery of the Higgs-boson. Due to the upcoming high energy and high luminosity phases of the Large Hadron Collider the precision of the measurements will increase. But the precision that is required to see important effects of physics beyond the Standard Model is presumably out of reach for the Large Hadron Collider. A possible future lepton collider could provide a precision allowing to either see those effects or rule out the theory that predicted them.
In this context the Higgsstrahlung process $e^+e^- \to HZ$ is an opportunity to measure Higgs properties model-independently using the recoil mass technique [1] and references therein. Using Higgsstrahlung it is possible to identify events only by measuring the Z boson, either hadronically from the momenta of the jets, or leptonically from the momenta of the leptons, which makes the measurement model-independent. At the LHC the dominant Higgs production is via gluon fusion, and hence one can only measure Higgs production times branching ratio. Identifying Higgsstrahlung events only by the jet momenta is not possible at hadron colliders such as the LHC, since there the cross sections of the background processes are too large. But at a lepton collider the background is small enough to apply this method. Thus, a lepton collider offers new ways to determine properties of the Higgs boson. It is, therefore, interesting to analyze the Higgsstrahlung process in order to obtain predictions for a future lepton collider such as the International Linear Collider (ILC).

In the following firstly the workflow of WHIZARD is explained and secondly the results of the Higgsstrahlung analysis are presented. The analysis mainly consists of the WHIZARD results and an attempt to verify those results using MadGraph.

2 Computational setup of WHIZARD

2.1 Why WHIZARD?

Supposing one would like to verify if a certain model of particle physics is correct, one has to get precise predictions for all sorts of observables. Typically these are cross sections and differential distributions of a certain process. Since there are usually multiple processes possible, it is important to also have a precise theoretical estimate of the background. It is convenient to hand such tasks to a software that performs the calculations automatically. This software is usually a Monte Carlo Event Generator and in our particular case we use WHIZARD [2].

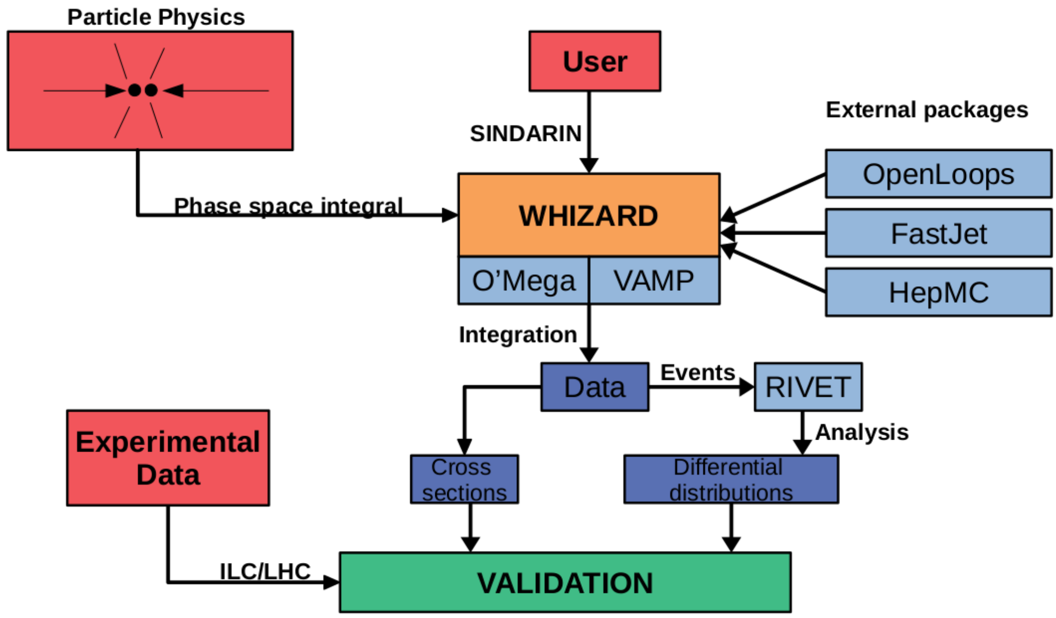

Figure 1: Workflow of Whizard [3].

2.2 Workflow of WHIZARD

The user controls WHIZARD using Sindarin, which is a language specifically designed to steer WHIZARD. Given a process and accordingly set options in the Sindarin file, WHIZARD performs the phase space integral to obtain the cross section of the specified process. The matrix elements that are used in the phase space integral are provided by the internal package `O'Mega` [4] in the LO case and by the external packages OpenLoops [5] or Recola [6, 7] in the NLO case. The phase space integral is performed by either `VAMP` or `VAMP2`. It is advisable to use `VAMP2` for any setup, since it is able to perform the integration parallel using MPI, whereas `VAMP` can only be used in single core calculations. After performing the phase space integral WHIZARD typically generates events, in our case for compatibility reasons in the HepMC format [8]. The computation of the cross section and the generation of events can be sped up significantly using either OpenMP or MPI. There are two requirements when executing WHIZARD parallel. As already mentioned `VAMP2` has to be chosen as an integrator. And secondly, the RNGStream Generator has to be used as a parallel-compatible random number generator. Since the outcome of the computations is to be compared with experimental data the result has to be physically well defined which requires clustering of jets. This task is performed by the external package FastJet [9]. WHIZARD is able to analyze generated LO events internally. However, analyzing NLO events has not yet been implemented in WHIZARD, which is why the generated events have to be fed into Rivet [10]. Rivet is able to perform a full analysis of NLO events. The obtained cross sections and distributions can then be compared to experimental data.

2.3 WHIZARD at NLO

There are three different terms that contribute to a next-to-leading order (NLO) calculation. The Born term is the contribution of the LO Feynman-diagram to NLO results. The virtual term represents contributions of loop diagrams. And the real term accounts for the emission of a soft or collinear gluon, meaning that there is one particle more in the final state than for the Born, so four particles for the process $e^+e^- \to Hjj$ that we are going to study.
In WHIZARD the integration of a process and the generation of the according events can be performed either combined or separately depending on the definition of the process. In order to have more control we decided to perform all three parts of the calculation separately. In Sindarin this corresponds to three different `process` definitions ending with

`{ nlo_calculation = <component> },` (1)

where `<component>` is either `born`, `real` or `virtual`. This leads to a total of three event samples. Each of the event samples has to be analyzed separately by Rivet. In the end the histograms of all three contributions have to be merged to give a single histogram, which requires that all three contributions have to be rescaled in a way that the normalization of each contribution matches the cross section of the respective contribution.

2.4 Further settings

There were some further settings which will be noted in the following.
The 4-flavor scheme was chosen, i.e. the Z-boson can not decay into the bottom- or top-quark and the respective anti-particles. As `jet_algorithm` the `antikt_algorithm` was used and the `jet_r` parameter was set to `0.5`. The factorization and renormalization scales were set to the mass of the Z-boson. And finally, the center-of-mass energy, $\sqrt{s}$, was chosen to be 350 GeV for reasons outlined in [1].

3 Results and comparison to MadGraph

In this section the results of the analysis of the Higgsstrahlung process are presented. They are compared to results that were obtained using MadGraph. The settings of MadGraph are chosen in such a way that they come as close as possible to the settings of WHIZARD. Some of the following diagrams show the k-factor, which is defined as

$$k = \frac{O_{\text{NLO}}}{O_{\text{LO}}}$$

for any observable O.

As one can see in table 1, the Higgsstrahlung cross sections at LO and NLO calculated with WHIZARD and MadGraph are, up to statistically insignificant differences, in good agreement with each other. In fig. 2 and 3 the distributions of transverse momentum of all jets and the hardest jet, i.e. the jet with the hardest transverse momentum, are shown at LO. The results of WHIZARD and MadGraph fit well to each other at LO. This implies together with the cross sections that the settings in MadGraph are compatible with the settings of WHIZARD.

By looking at fig. 4 and 5 it becomes obvious that WHIZARD and MadGraph do not agree with each other at NLO. This means that either the calculation of WHIZARD or MadGraph or both are wrong or there are certain settings not compatible between WHIZARD and MadGraph. Note that in case the MadGraph calculations are wrong, it is possible that we did not steer MadGraph correctly. As to the setting that could be incompatible: Such a setting can solely apply to the part of the calculation that is specific to the NLO calculation. This setting could be, for instance, the cut that is applied to the third hardest jet, which is less restrictive compared to the cut applied to the hardest and second hardest jet. A third hardest jet is only possible at NLO and does not need to have more than 30 GeV of transverse momentum according to the applied cuts that read

```
cuts = let subevt @clustered_jets = cluster [jet] in
    let subevt @pt_selected = select if Pt > 30 GeV [@clustered_jets] in
    let subevt @eta_selected = select if abs(Eta) < 4 [@pt_selected] in
    count [@eta_selected] >= 2.
```

That is different from the hardest and second hardest jet, which occur at LO and NLO and need to have at least 30 GeV of transverse momentum (cf. fig. 2).

There are two aspects of the MadGraph distributions that give reason to assume that the calculations at NLO performed by MadGraph can not be entirely correct. Firstly, as one can see in fig. 4 and especially in fig. 5, there are parts of the MadGraph distributions that are negative. This is unphysical. Secondly, there is no feature at 30 GeV in the NLO distribution of all jets calculated by MadGraph as can be seen in fig. 4 and 6. But there ought to be a feature since this is the minimum transverse momentum for the hardest and second hardest jet. In contrast to the MadGraph distribution at NLO such a feature can be seen in the WHIZARD distribution at NLO (cf. fig. 4 and 8).

Coming back to our three possible explanations for the fact that WHIZARD and MadGraph give different results it seems to be most likely that the calculations of MadGraph are not correct. That does not mean that the WHIZARD results are wrong. But it also means that there is no way to verify the WHIZARD results using MadGraph at the moment.

Table 1: Cross sections of the Higgsstrahlung process with hadronic decay. The results were obtained at LO and NLO using WHIZARD and MadGraph. The given uncertainties denote the numerical uncertainty provided by the respective software. All cross sections are given in fb.

	LO	NLO
WHIZARD	45.441±0.007	44.66±0.03
MadGraph	45.26±0.06	44.60±0.04

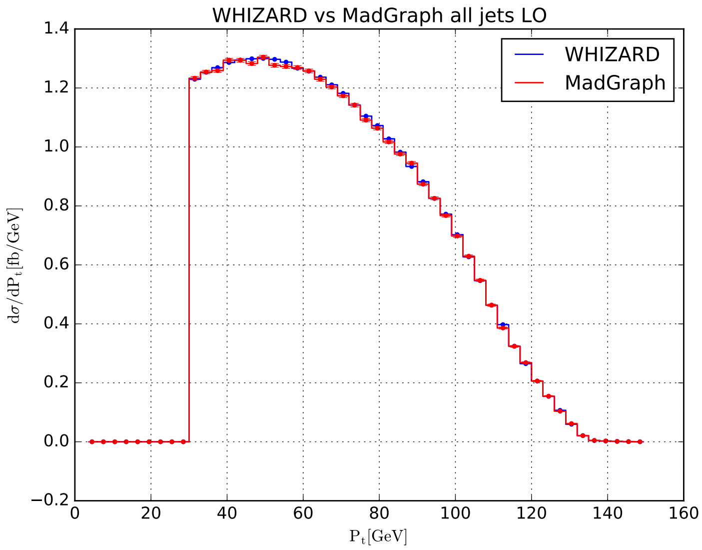

Figure 2: Histogram of the transverse momentum of all jets, i.e. the hardest and second hardest jets are contributing to the histogram. The used events are based on a LO calculation performed with MadGraph and WHIZARD, respectively.

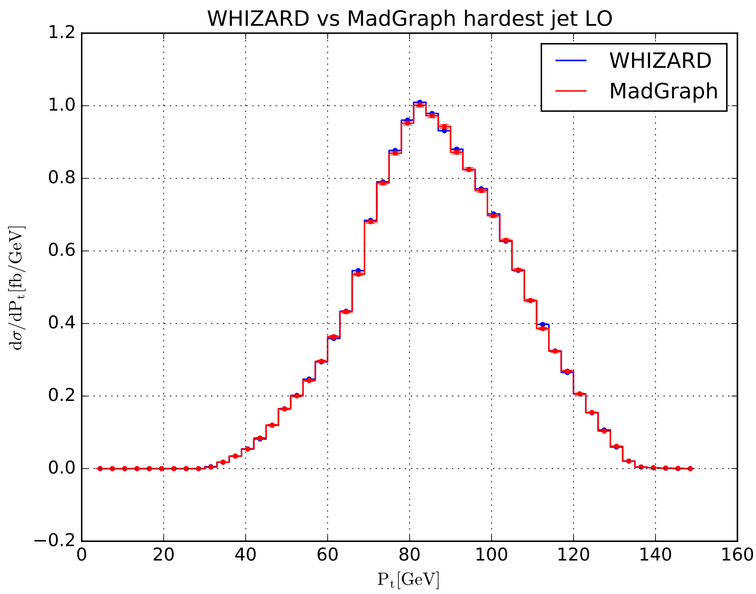

Figure 3: Histogram of the transverse momentum of the hardest jet. The used events are based on a LO calculation performed with MadGraph and WHIZARD, respectively.

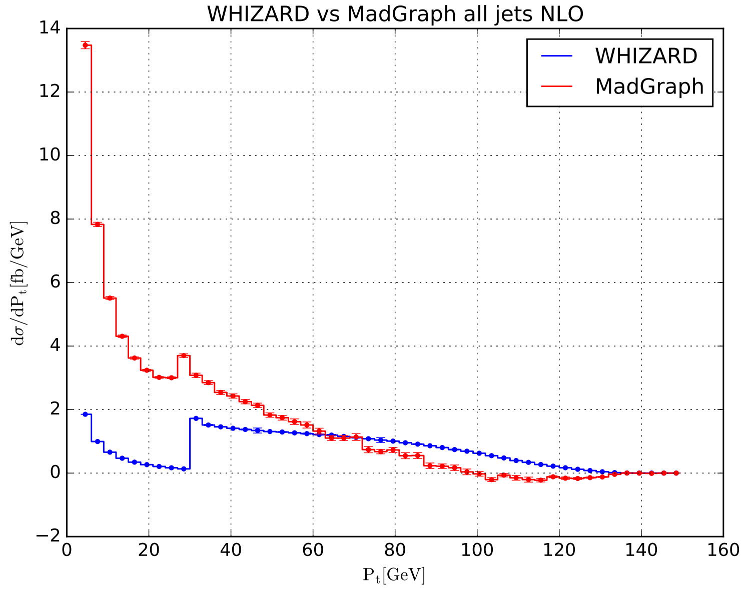

Figure 4: Histogram of the transverse momentum of all jets, i.e. the hardest and second hardest jets are contributing to the histogram as well as the possible third hardest jet. The used events are based on a NLO calculation performed with MadGraph and WHIZARD, respectively. The total number of three jets is possible due to real emission at NLO.

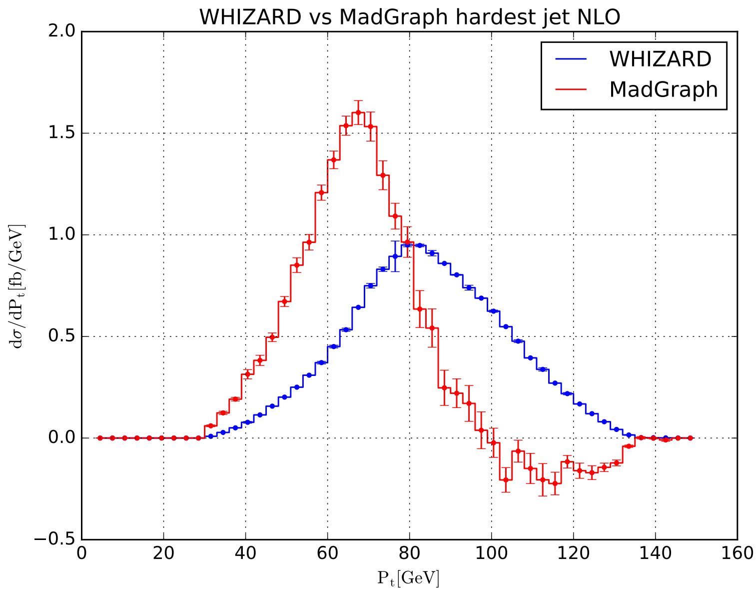

Figure 5: Histogram of the transverse momentum of the hardest jet. The used events are based on a NLO calculation performed with MadGraph and WHIZARD, respectively.

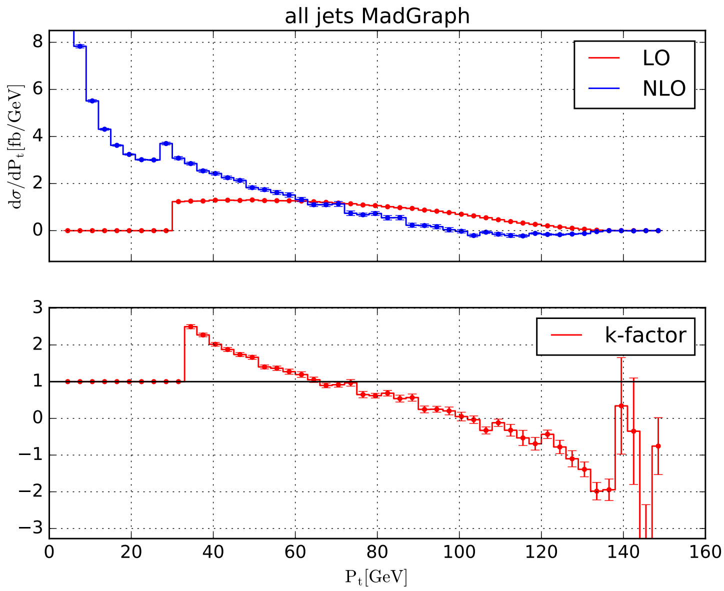

Figure 6: Histograms of the transverse momentum of all jets, i.e. the hardest and second hardest jets are contributing to the histogram as well as the possible third hardest jet. The used events are based on a LO and NLO calculation, respectively, performed with MadGraph. The total number of three jets is possible due to real emission at NLO.

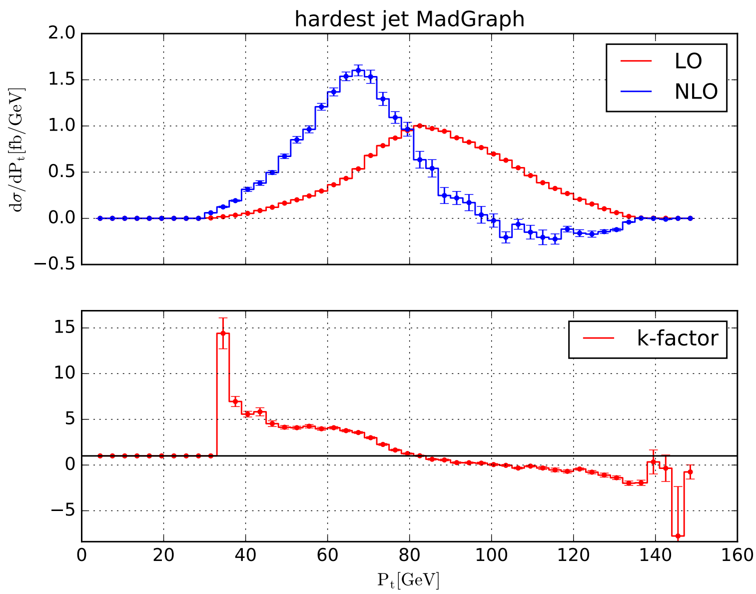

Figure 7: Histograms of the transverse momentum of the hardest jet. The used events are based on a LO and NLO calculation, respectively, performed with MadGraph.

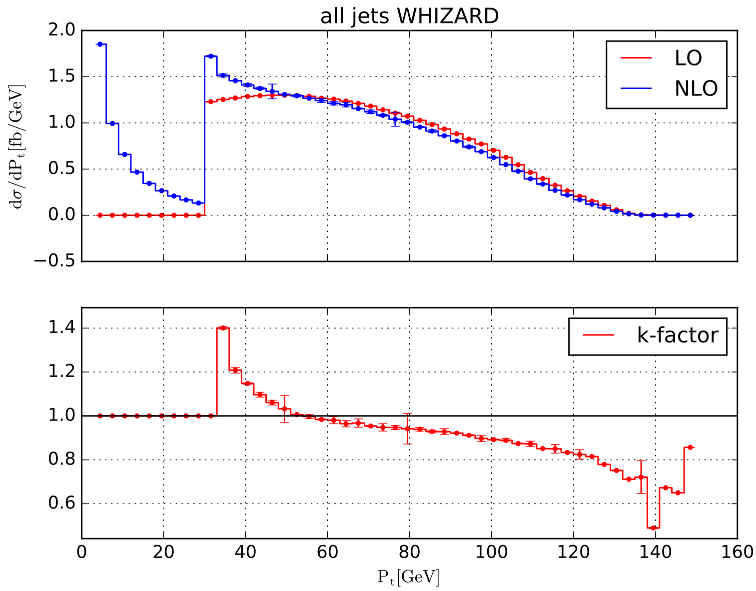

Figure 8: Histograms of the transverse momentum of all jets, i.e. the hardest and second hardest jets are contributing to the histogram as well as the possible third hardest jet. The used events are based on a LO and NLO calculation, respectively, performed with WHIZARD. The total number of three jets is possible due to real emission at NLO.

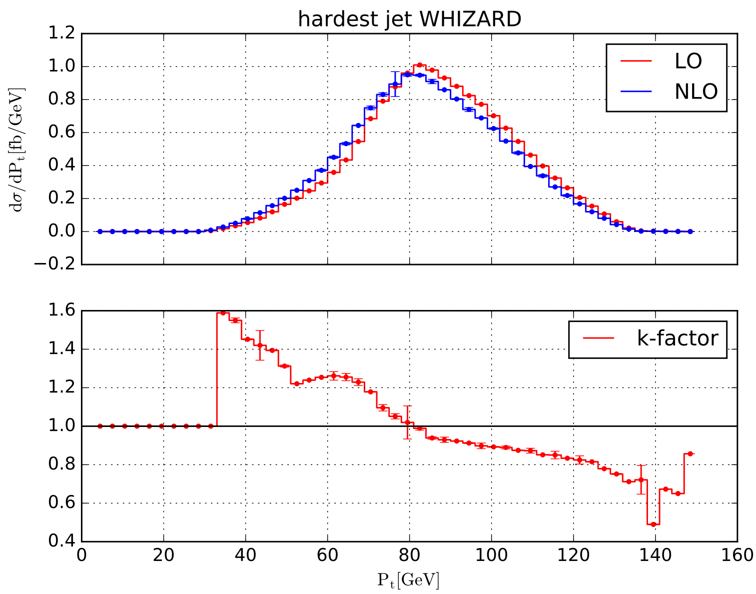

Figure 9: Histograms of the transverse momentum of the hardest jet. The used events are based on a LO and NLO calculation, respectively, performed with WHIZARD.

4 Conclusion and outlook

We have calculated cross sections and differential distributions of the Higgsstrahlung process with hadronic Z decay. The calculations were performed at both LO and NLO QCD and using both WHIZARD and MadGraph. While the cross sections and the differential distributions at LO of WHIZARD and MadGraph are in good agreement with each other, there are differences in the differential distributions at NLO. We concluded that the distributions calculated using MadGraph are not correct. In contrast to that, the WHIZARD distributions have reasonable features. But since the MadGraph distributions are not correct it is impossible to verify the WHIZARD results using the MadGraph results.
In future work it could be tried to resolve the issues that remain regarding the MadGraph differential distributions at NLO. That would allow to fully verify the results of WHIZARD.
After having verified differential distributions, it would be interesting to apply the obtained k-factors to LO distributions that were obtained using BSM models. If the used BSM model changes only the HZ coupling in the considered process, it is reasonable to assume that differential distributions of the BSM model at LO combined with the SM k-factors give a good approximation of differential distributions and cross sections of the BSM model at NLO.

References

[1] M. Thomson, *Model-independent measurement of the $e^+ e^- \rightarrow HZ$ cross section at a future $e^+ e^-$ linear collider using hadronic Z decays*, *Eur. Phys. J.* **C76** (2016) 72 , `arXiv:1509.02853 [hep-ex]`.

[2] W. Kilian, T. Ohl and J. Reuter, *WHIZARD: Simulating Multi-Particle Processes at LHC and ILC*, *Eur. Phys. J.* **C71** (2011) 1742 , `arXiv:0708.4233 [hep-ph]`.

[3] M. Niedermeier, *Precision study at NLO QCD for semi leptonic Di-boson processes at future Linear Colliders*, Bachelor's Thesis, Ludwig-Maximilians-Universität München, DESY Hamburg.

[4] M. Moretti, T. Ohl and J. Reuter, *O'Mega: An Optimizing matrix element generator*, `arXiv:hep-ph/0102195 [hep-ph]`.

[5] F. Buccioni, J.-N. Lang, J. M. Lindert, P. Maierhöfer, S. Pozzorini et al., *OpenLoops 2*, `arXiv:1907.13071 [hep-ph]`.

[6] S. Actis, A. Denner, L. Hofer, A. Scharf and S. Uccirati, *Recursive generation of one-loop amplitudes in the Standard Model*, *JHEP* **04** (2013) 037 , `arXiv:1211.6316 [hep-ph]`.

[7] S. Actis, A. Denner, L. Hofer, J.-N. Lang, A. Scharf et al., *RECOLA: REcursive Computation of One-Loop Amplitudes*, *Comput. Phys. Commun.* **214** (2017) 140 , `arXiv:1605.01090 [hep-ph]`.

[8] M. Dobbs and J. B. Hansen, *The HepMC C++ Monte Carlo event record for High Energy Physics*, *Comput. Phys. Commun.* **134** (2001) 41.

[9] M. Cacciari, G. P. Salam and G. Soyez, *FastJet User Manual*, *Eur. Phys. J.* **C72** (2012) 1896 , `arXiv:1111.6097 [hep-ph]`.

[10] A. Buckley, J. Butterworth, L. Lonnblad, D. Grellscheid, H. Hoeth et al., *Rivet user manual*, *Comput. Phys. Commun.* **184** (2013) 2803 , `arXiv:1003.0694 [hep-ph]`.