PROCEEDINGS OF SCIENCE

PoS(LHCP2022)183

Vector-Boson Scattering at the LHC – Recent Theory Developments

---

Barbara Jäger*

Institute for Theoretical Physics, University of Tübingen,
Auf der Morgenstelle 14, 72076 Tübingen, Germany

E-mail: `barbara.jaeger@itp.uni-tuebingen.de`

Vector-boson scattering processes are at the heart of the physics program of the CERN Large Hadron Collider. This short contribution aims at giving a review on recent precision calculations for this important class of reactions. After a survey of fixed-order perturbative calculations the status of their matching to parton-shower programs is summarized. A brief outlook on new avenues in the exploration of vector-boson scattering completes the contribution.

The Tenth Annual Conference on Large Hadron Collider Physics - LHCP2022
16-20 May 2022
online

---

[*] Speaker

1. Introduction

Vector boson fusion (VBS) processes are at the heart of the physics program of the CERN Large Hadron Collider (LHC). With their sensitivity to triple and quartic gauge couplings in the electroweak sector, and to the mechanism of electroweak symmetry breaking itself they are ideally suited to identify signatures of – or set limits on – physics beyond the Standard Model (SM) in the EW sector. However, unambiguously identifying hints of new physics in this class of reactions requires precise predictions in the framework of the SM. Modern calculations accounting for various types of fixed-order perturbative corrections and parton shower effects are often implemented in flexible Monte-Carlo programs that can be adapted to the users' needs. It is the scope of this short contribution to provide a brief review of such calculations and tools, and urge experimentalists to implement this state-of-the art machinery in their analyses of LHC data.

2. Precision calculations

At the LHC, VBS processes are accessed in the scattering of (anti-)quarks by the exchange of EW bosons in the t channel with subsequent weak gauge-boson emission. The cleanest signatures are provided by leptonic decay modes resulting in final states with four leptons (charged leptons or neutrinos) and two tagging jets. The same final state can result from singly- and non-resonant diagrams at the sixth order of the EW coupling, but also from QCD contributions and their interference with the EW production mode, giving rise to tree-level components at $O(\alpha_s^2\alpha^4)$ and $O(\alpha_s\alpha^5)$.

Early calculations of the next-to-leading order (NLO) QCD corrections to VBS processes [1–5] concentrated on the pure EW production mode. They relied on the VBS approximation which captures the main contributions very well when VBS-specific selection cuts are applied that require the presence of two tagging jets of large invariant mass and rapidity separation. The actual size of the NLO-QCD corrections depends on factorization and renormalization scales as well as on the choice of selection cuts, but is generally moderate. For each VBS channel an implementation is provided in the framework of the publicly available parton-level Monte-Carlo program `VBFNLO` [6]. NLO-QCD corrections to the QCD-induced production of four leptons and two jets have been computed in Refs. [7–12] and found to significantly reduce the dependence of predictions on factorization and renormalization scales.

More recently, the NLO-QCD and EW corrections to the various $pp \to 4$ leptons + 2 jets processes have been tackled in full with the help of the amplitude generator `RECOLA` [13, 14]. In Refs. [15, 16] the complete NLO-QCD and EW corrections to $pp \to \mu^+\nu_\mu e^+\nu_e jj$ have been computed, followed by similar calculations for $pp \to \mu^-\mu^+e^+\nu_e jj$ [17], $pp \to \mu^-\mu^+e^+e^- jj$ [18, 19], and $pp \to \mu^+\nu_\mu e^-\bar{\nu}_e jj$ [20]. Depending on channel and setup, the size of the EW corrections can compete with and in some cases even exceed the NLO-QCD corrections.

3. Matching to parton showers

While precision calculations aim at advancing the accuracy of the hard scattering processes, experimental analyses rely on the versatile machinery of multi-purpose Monte-Carlo generators that provide parton showers and features for the description of non-perturbative effects such as hadronization, underlying event, or multi-parton interactions. A matching of higher-order perturbative corrections with parton showers is thus of paramount importance to allow for, at the same time, accurate and realistic simulations for scattering processes at hadron colliders. With the advent of the `MC@NLO` [21] and `POWHEG` [22, 23] algorithms for the matching of NLO calculations with parton showers the theoretical prerequisites for this enterprise have been put in place. Practical implementations of the `POWHEG` scheme are possible in the framework of the `POWHEG BOX` [24] which provides general routines for the matching of fixed-order calculations with parton showers and merely requires process-specific elements for each considered scattering process. For the fully leptonic decay modes of all VBS processes (and for the semi-leptonic decay modes of selected channels) `POWHEG BOX` implementations are available. An alternative implementation of the EW production process $pp \to \mu^+\nu_\mu e^-\bar{\nu}_e jj$ has been presented in Ref. [25] resorting to the `HERWIG7` framework [26]. Generally, the parton-shower has little impact on distributions related to the hard tagging jets comprising the VBS signature, but can significantly affect subleading jets, in particular, if a sub-optimal recoil scheme is used in the parton-shower generator. The latter effect was recently discussed for the related process of Higgs production via vector boson fusion and found to be mitigated in `PYTHIA` [27–29] when a dipole recoil scheme is used instead of a global recoil scheme [30].

Employing tools that, at the same time, take into account NLO-QCD corrections and allow for a matching to parton-shower generators becomes particularly relevant when observables involving subleading jets are considered or used as input in VBS analyses. Signal-to-background ratios in VBS searches can be improved by a so-called *central jet veto* (CJV), i.e. disregarding events that in addition to the two tagging jets defining the VBS signature feature more hard jets in the central-rapidity region. Such analyses rely on a precise understanding of the subleading jets' behavior. However, if LO matrix elements are employed for the simulation of a VBS process in conjunction with a parton shower, such subleading jets can be generated only by the parton shower – which by definition is reliable only in the soft / collinear regions and thus not capable to account for hard jets. The poor predictive power of such simulations is nicely illustrated by a tuned comparison of LO tools for the EW $\nu_e e^+\mu^-\mu^+ jj$ production process [31] which found strongly differing results for distributions related to a third jet. If NLO-QCD corrections are taken into account, a hard third jet can also stem from the real-emission contributions. Figure 1 illustrates for a representative setup (see Ref. [32] for details) how predictions for the rapidity of the third jet in an NLO+PS simulation exhibit a much milder dependence on details of the parton-shower generator than those reported in the LO study of Ref. [31] .

A matching of the NLO-EW corrections to the same-sign VBS process with a QED shower in the context of the `POWHEG BOX` has been achieved in [33]. In particular, in the tails of transverse-momentum and invariant-mass distributions such shower effects tend to enhance the negative impact of the NLO-EW corrections on the corresponding tree-level results.

4. Polarization observables

In the context of the SM, the weak gauge bosons receive their masses and longitudinal polarization degrees of freedom via the Higgs mechanism. The scattering of longitudinal gauge bosons

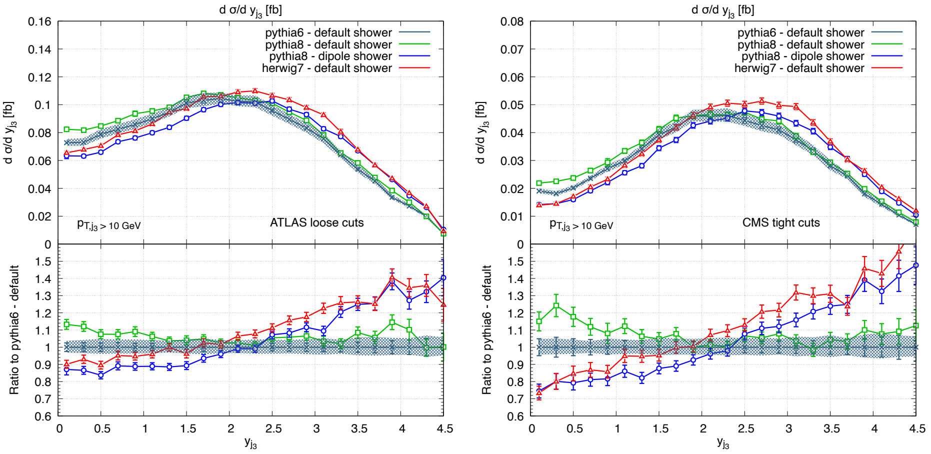

Figure 1: *Rapidity distribution of the third jet in EW $\nu_e e^+\mu^-\mu^+ jj$ production at NLO-QCD accuracy matched with* `HERWIG7` *(red),* `PYTHIA6` *(grey), and* `PYTHIA8` *with either a global (green) or a dipole (blue) recoil scheme, for two different sets of selection cuts. In the lower panels the ratios of the respective distributions to the* `PYTHIA6` *reference result are shown. Adapted from Ref. [32].*

is unitarized by a subtle interplay between weak boson and Higgs contributions. New physics affecting this interplay may give rise to unitarity violations in weak boson scattering cross sections. Directly accessing specific polarization states of the vector bosons thus provides an extra handle on identifying signatures of new physics in the EW sector.

The definition of specific polarization states is highly non-trivial in the realistic environment of VBS searches at the LHC. First and foremost, vector bosons are unstable particles that cannot be directly accessed. Information on their polarization is passed on to their decay products. However, part of this information is lost unless the respective decay angles are fully integrated over and no cuts are imposed. Additionally, vector bosons can be produced off-shell. In this case, a momentum projection onto their mass shell can be applied. In a realistic $pp \to 4$ leptons+2 jets process not only diagrams with two weak gauge bosons decaying into leptons appear, but also non-resonant diagrams occur. Simply disregarding them would spoil gauge invariance. Finally, since polarization vectors are not Lorentz covariant, a particular reference frame must be chosen. Despite these technical complications some progress has been made in the simulation of polarization observables in VBS processes [34–37].

5. Conclusions and outlook

VBS processes represent a class of reactions crucial to an understanding of the electroweak sector of the SM and to identifying possible signatures of new physics in this domain. Despite the technical complexity represented by a scattering process with as many as six particles in the final state at tree level already, a wealth of advanced precision calculations exists accounting for NLO-QCD and EW corrections as well as for parton-shower effects. Public tools are available for the simulation of all production channels with fully leptonic and for selected semi-leptonic and hadronic decay modes. They can unfold their full potential only if used in all experimental analyses.

Acknowledgments

The invitation to present a talk at the 10th Annual Large Hadron Collider Physics Conference is greatly appreciated. Support by BMBF through grant no. 05H21VTCAA and by the state of Baden-Württemberg through bwHPC and the German Research Foundation (DFG) through grant no INST 39/963-1 FUGG is gratefully acknowledged.

References

[1] B. Jager, C. Oleari and D. Zeppenfeld, *Next-to-leading order QCD corrections to W+W- production via vector-boson fusion*, *JHEP* **07** (2006) 015 [`hep-ph/0603177`].

[2] B. Jager, C. Oleari and D. Zeppenfeld, *Next-to-leading order QCD corrections to Z boson pair production via vector-boson fusion*, *Phys. Rev. D* **73** (2006) 113006 [`hep-ph/0604200`].

[3] G. Bozzi, B. Jager, C. Oleari and D. Zeppenfeld, *Next-to-leading order QCD corrections to W+ Z and W- Z production via vector-boson fusion*, *Phys. Rev. D* **75** (2007) 073004 [`hep-ph/0701105`].

[4] B. Jager, C. Oleari and D. Zeppenfeld, *Next-to-leading order QCD corrections to W+ W+ jj and W- W- jj production via weak-boson fusion*, *Phys. Rev. D* **80** (2009) 034022 [`0907.0580`].

[5] A. Denner, L. Hosekova and S. Kallweit, *NLO QCD corrections to W+ W+ jj production in vector-boson fusion at the LHC*, *Phys. Rev. D* **86** (2012) 114014 [`1209.2389`].

[6] K. Arnold et al., *VBFNLO: A Parton level Monte Carlo for processes with electroweak bosons*, *Comput. Phys. Commun.* **180** (2009) 1661 [`0811.4559`].

[7] T. Melia, K. Melnikov, R. Rontsch and G. Zanderighi, *Next-to-leading order QCD predictions for* W^+W^+jj *production at the LHC*, *JHEP* **12** (2010) 053 [`1007.5313`].

[8] T. Melia, K. Melnikov, R. Rontsch and G. Zanderighi, *NLO QCD corrections for* W^+W^- *pair production in association with two jets at hadron colliders*, *Phys. Rev. D* **83** (2011) 114043 [`1104.2327`].

[9] N. Greiner, G. Heinrich, P. Mastrolia, G. Ossola, T. Reiter and F. Tramontano, *NLO QCD corrections to the production of W+ W- plus two jets at the LHC*, *Phys. Lett. B* **713** (2012) 277 [`1202.6004`].

[10] F. Campanario, M. Kerner, L. D. Ninh and D. Zeppenfeld, *WZ Production in Association with Two Jets at Next-to-Leading Order in QCD*, *Phys. Rev. Lett.* **111** (2013) 052003 [`1305.1623`].

[11] F. Campanario, M. Kerner, L. D. Ninh and D. Zeppenfeld, *Next-to-leading order QCD corrections to* W^+W^+ *and* W^-W^- *production in association with two jets*, *Phys. Rev. D* **89** (2014) 054009 [`1311.6738`].

[12] F. Campanario, M. Kerner, L. D. Ninh and D. Zeppenfeld, *Next-to-leading order QCD corrections to ZZ production in association with two jets*, *JHEP* **07** (2014) 148 [`1405.3972`].

[13] S. Actis, A. Denner, L. Hofer, J.-N. Lang, A. Scharf and S. Uccirati, *RECOLA: REcursive Computation of One-Loop Amplitudes*, *Comput. Phys. Commun.* **214** (2017) 140 [`1605.01090`].

[14] A. Denner, J.-N. Lang and S. Uccirati, *Recola2: REcursive Computation of One-Loop Amplitudes 2*, *Comput. Phys. Commun.* **224** (2018) 346 [`1711.07388`].

[15] B. Biedermann, A. Denner and M. Pellen, *Large electroweak corrections to vector-boson scattering at the Large Hadron Collider*, *Phys. Rev. Lett.* **118** (2017) 261801 [`1611.02951`].

[16] B. Biedermann, A. Denner and M. Pellen, *Complete NLO corrections to W^+W^+ scattering and its irreducible background at the LHC*, *JHEP* **10** (2017) 124 [`1708.00268`].

[17] A. Denner, S. Dittmaier, P. Maierhöfer, M. Pellen and C. Schwan, *QCD and electroweak corrections to WZ scattering at the LHC*, *JHEP* **06** (2019) 067 [`1904.00882`].

[18] A. Denner, R. Franken, M. Pellen and T. Schmidt, *NLO QCD and EW corrections to vector-boson scattering into ZZ at the LHC*, *JHEP* **11** (2020) 110 [`2009.00411`].

[19] A. Denner, R. Franken, M. Pellen and T. Schmidt, *Full NLO predictions for vector-boson scattering into Z bosons and its irreducible background at the LHC*, *JHEP* **10** (2021) 228 [`2107.10688`].

[20] A. Denner, R. Franken, T. Schmidt and C. Schwan, *NLO QCD and EW corrections to vector-boson scattering into W^+W^- at the LHC*, *JHEP* **06** (2022) 098 [`2202.10844`].

[21] S. Frixione and B. R. Webber, *Matching NLO QCD computations and parton shower simulations*, *JHEP* **06** (2002) 029 [`hep-ph/0204244`].

[22] P. Nason, *A New method for combining NLO QCD with shower Monte Carlo algorithms*, *JHEP* **11** (2004) 040 [`hep-ph/0409146`].

[23] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with Parton Shower simulations: the POWHEG method*, *JHEP* **11** (2007) 070 [`0709.2092`].

[24] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, *JHEP* **06** (2010) 043 [`1002.2581`].

[25] M. Rauch and S. Plätzer, *Parton Shower Matching Systematics in Vector-Boson-Fusion WW Production*, *Eur. Phys. J. C* **77** (2017) 293 [`1605.07851`].

[26] J. Bellm et al., *Herwig 7.0/Herwig++ 3.0 release note*, *Eur. Phys. J. C* **76** (2016) 196 [`1512.01178`].

[27] T. Sjostrand, S. Mrenna and P. Z. Skands, *PYTHIA 6.4 Physics and Manual*, *JHEP* **05** (2006) 026 [`hep-ph/0603175`].

[28] T. Sjostrand, S. Mrenna and P. Z. Skands, *A Brief Introduction to PYTHIA 8.1*, *Comput. Phys. Commun.* **178** (2008) 852 [`0710.3820`].

[29] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten et al., *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159 [`1410.3012`].

[30] S. Höche, S. Mrenna, S. Payne, C. T. Preuss and P. Skands, *A Study of QCD Radiation in VBF Higgs Production with Vincia and Pythia*, *SciPost Phys.* **12** (2022) 010 [`2106.10987`].

[31] *Les Houches 2017: Physics at TeV Colliders Standard Model Working Group Report*, 3, 2018.

[32] B. Jager, A. Karlberg and J. Scheller, *Parton-shower effects in electroweak $WZjj$ production at the next-to-leading order of QCD*, *Eur. Phys. J. C* **79** (2019) 226 [`1812.05118`].

[33] M. Chiesa, A. Denner, J.-N. Lang and M. Pellen, *An event generator for same-sign W-boson scattering at the LHC including electroweak corrections*, *Eur. Phys. J. C* **79** (2019) 788 [`1906.01863`].

[34] A. Ballestrero, E. Maina and G. Pelliccioli, *W boson polarization in vector boson scattering at the LHC*, *JHEP* **03** (2018) 170 [`1710.09339`].

[35] A. Ballestrero, E. Maina and G. Pelliccioli, *Polarized vector boson scattering in the fully leptonic WZ and ZZ channels at the LHC*, *JHEP* **09** (2019) 087 [`1907.04722`].

[36] A. Ballestrero, E. Maina and G. Pelliccioli, *Different polarization definitions in same-sign WW scattering at the LHC*, *Phys. Lett. B* **811** (2020) 135856 [`2007.07133`].

[37] D. Buarque Franzosi, O. Mattelaer, R. Ruiz and S. Shil, *Automated predictions from polarized matrix elements*, *JHEP* **04** (2020) 082 [`1912.01725`].