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# Precise predictions for same sign W-bosons scattering at the LHC


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**Abstract**

In this article, a detailed study of the vector-boson scattering of two positively charged W bosons is presented. In particular, a comparison between the full NLO QCD corrections against several approximations is carried out. This study is not only performed in the usual fiducial region used by experimental collaborations but also in a more inclusive set-up. This allows to infer precisely the quality of such approximations. Finally, NLO predictions matched to various parton shower are discussed. This study allows thus to infer the systematics related to vector-boson scattering at the NLO-QCD level and beyond.

# Contents

# 1 Introduction

The vector-boson scattering (VBS) process with two positively charged W boson is just starting to be measured at the LHC [1–3]. A whole class of new processes will therefore be measured during Run II at the Large Hadron Collider (LHC). For now the measurements of VBS processes are limited by statistics but the situation will change in a near future. On the theoretical side, it is thus of prime importance to provide precise predictions and infer their related systematics.

The $\mathrm{W}^+\mathrm{W}^+$ scattering is probably the simplest VBS processes to compute and to measure due to its particular charge structure and low background, respectively. Therefore, it is an ideal example for a detailed study of various theoretical predictions. In the last few years, several (N)LO computations become available for both the VBS process [4–7] and its QCD-induced irreducible background process [8–11, 7]. These computations all relied on approximations while recently the complete NLO corrections became available [12]. It is therefore interesting to infer in details the quality of the various approximations. Indeed, apart from Ref. [12] [MP: more references?] no detailed comparison of the VBS approximations have been carried out.

The hadronic process is $\mathrm{pp} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ and it posses three contributions at leading order (LO) [$\mathcal{O}(\alpha^6)$, $\mathcal{O}(\alpha_\mathrm{s}^2\alpha^4)$, and $\mathcal{O}(\alpha_\mathrm{s}\alpha^5)$]. They are refer to as EW, interference, and QCD contributions respectively. The EW contribution is sometimes referred to as the VBS contribution even it possesses not-VBS contributions. Therefore, we start with a LO study of these contributions as a function of typical VBS cuts. This allows to understand the various contributions to the final state $\mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$. This is followed by a LO comparison between the various predictions at the level of the cross section and differential distributions.

At NLO, the process possesses four contributions of orders $\mathcal{O}(\alpha^7)$, $\mathcal{O}(\alpha_\mathrm{s}\alpha^6)$, $\mathcal{O}(\alpha_\mathrm{s}^2\alpha^5)$, and $\mathcal{O}(\alpha_\mathrm{s}^3\alpha^4)$. The largest one is the EW corrections of order $\mathcal{O}(\alpha^7)$ [13, 12]. The contribution of order $\mathcal{O}(\alpha_\mathrm{s}\alpha^6)$ is the second largest NLO contribution. It is often referred as the QCD corrections to the VBS process. In the following, this order is the one where our comparisons are focused on. It is therefore usually referred to as simply *NLO*. As for the LO study, the various predictions are compared at the level of the cross section and differential distributions.

Finally, several predictions featuring parton shower are compared. This allows to infer systematics differences between the various predictions. This is the first time in the literature that such an analysis has been carried out [MP: True?] .

Obviously all VBS processes deserve such a study but the present article sets the standard for inferring systematics related to NLO corrections and beyond.

The article is organised as follow: in the first part (section 2), the process studied is defined. Then, various approximation at LO and NLO are described in section 3. It is followed by a presentation of the various programs used for the simulations. Sections 4 and 5 are devoted to a LO and NLO study, respectively. Section 6 deals with the matching to parton shower. The last section (section 7) consists in concluding remarks and recommendations.

# 2 Definition of the process

Definition of the process.
Explaining the various contributions.
Show few Feynman diagrams and explain that it possesses also tri-boson contributions in the s-channel.
This is explained in some details in Ref. [12].

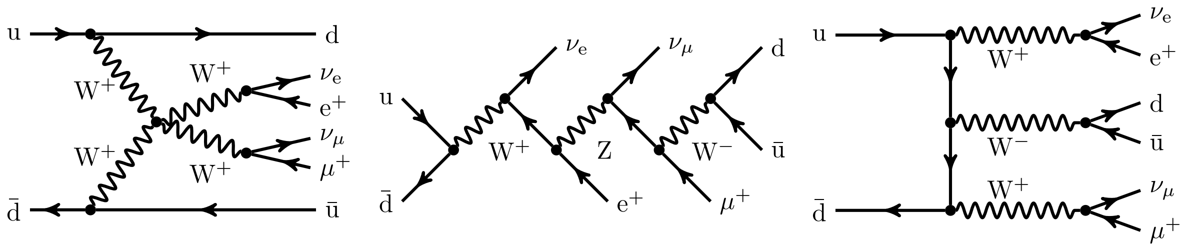


Figure 1: Sample tree-level diagrams that contribute to the process $\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ at order $\mathcal{O}(\alpha^6)$. In addition to typical VBS contribution (left), this order also possesses $s$-channel (middle) and tri-boson contributions (right).

# 3 Details of the calculations

## 3.1 Several descriptions for one process

Describe the physics and mention the code that simulate these cases.
Start with LO (one paragraph each).

- Details on the description starting from the VBS approximation which we define as the t-u approximation (other names in the litterature)
Start from the idea of two independent protons etc. (POWHEG)
- adding $s$-channel contributions, explain why this is possible to add them separately (VBFNLO)
- Full computation (MG, MoCaNLO-Recola, Phantom)

Move to NLO (one paragraph each).

- VBS approximation at NLO (POWHEG)
- VBS approximation at NLO + DPA for virt (Bonsay)
- VBS approximation + $s$-channel (VBS NLO)
- Hybrid VBS approximation (MG)
- Explanation why EW corrections are needed in the full computation (Recola)

[MP: Part written by Giovanni to be included]

The VBS approximation [?] is frequently employed for VBS computations and we aim at the identification of kinematical regions where it provides trustworthy prediction for the $W^+W^+$ scattering. At LO, given the full set of diagrams contributing at order $\mathcal{O}(\alpha_{ew}^6)$, the approximations consists in:

- discarding interferences between $t$ and $u$ channel diagrams, which are expected to be suppressed in the fiducial volume, after VBF cuts;
- discarding $s$–channel diagrams shown in **??**, which contain $q\bar{q}'$ annihilations ($W^- \to q\bar{q}'$); with a hard cut on the $jj$–pair invariant mass, these contributions are strongly suppressed.

## 3.2 Description of the predictions

In the comparison, the following codes are used:

- The program Bonsay consists of a general-purpose Monte Carlo integrator and matrix elements taken from several sources: Born matrix elements are adapted from the program Lusifer [14] for the partonic processes, real matrix elements are written by Marina Billoni, and virtual matrix elements by Stefan Dittmaier. One loop integrals are evaluated using the Collier library [15, 16].

- MadGraph5_aMC@NLO [17] is an automatic meta-code (a code that generates codes) which makes it possible to simulate any scattering process including NLO QCD corrections both at fixed order and including matching to parton showers. It makes use of the FKS subtraction method [18, 19] (automated in the module MadFKS [20, 21]) for regulating IR singularities. The computationsof one-loop amplitudes are carried out by switching dynamically between two integral-reduction techniques, OPP [22] or Laurent-series expansion [23], and TIR [24–26]. These have been automated in the module MadLoop [27], which in turn exploits CutTools [28], Ninja [29, 30], or IREGI [31], together with an in-house implementation of the OpenLoops optimisation [32].
  The simulation of VBS at NLO-QCD accuracy can be performed by issuing the following commands in the program interface:

```
> set complex_mass_scheme #1
> import model loop_qcd_qed_sm_Gmu #2
> generate p p > e+ ve mu+ vm j j QCD=0 [QCD] #3
> output #4
```

  With these commands the complex-mass scheme is turned on `#1`, then the NLO-capable model is loaded `#2`[1], finally the process code is generated `#3` (note the `QCD=0` syntax to select the purely-electroweak process) and written to disk `#4`. Because of some internal limitations, which will be lifted in the future version capable of computing both QCD and EW corrections, only loops with QCD-interacting particles are generated. [MP: Detail of the approximation done, divergent part, assumed to cancel etc.]

- Phantom [33] is a dedicated tree–level Monte Carlo for six parton final states at $pp$, $p\bar{p}$ and $e^+e^-$ colliders at $\alpha_{ew}^6$ and $\alpha_{ew}^4\alpha_s^2$ including interferences between the two sets of diagrams. It employs complete tree–level matrix elements in the complex–mass scheme [34] computed via the modular helicity formalism [35, 36]. The integration uses a multichannel approach [37] and an adaptive strategy [38]. Phantom generates unweighted events at parton–level for both the SM and a few instances of BSM theories..

- The Powheg-Box [39, 40] is a framework for mathcing NLO-QCD calculations with parton showers. It relies on the user providing the matrix elements and Born phase space, but will automaticaly construct FKS [18] subtraction terms and the phase space for the real emission. For the VBS processes all matrix elements are being provided by a previous version of VBFNLO [41, 42, 11] and hence the approximations used in the Powheg-Box are the similar to those used in VBFNLO. [MP: Mention the non-clustering for the scale as well as the different running of alphas at NLO.]

[1] Despite the `loop_qcd_qed_sm_Gmu` model also includes NLO counterterms for computing electro-weak corrections, it is not yet possible to compute such corrections with the current version of the code.

| Code | $\mathcal{O}(\alpha^6)$ $\lvert s\rvert^2$/ $\lvert t\rvert^2/\lvert u\rvert^2$ | $\mathcal{O}(\alpha^6)$ interf. | Non-res. | NLO | NF QCD | EW corr. to $\mathcal{O}(\alpha^5\alpha_s)$ |
|---|---|---|---|---|---|---|
| Bonsay | $t/u$ | No | Yes, virt. No | Yes | No | No |
| POWHEG | $t/u$ | No | Yes | Yes | No | No |
| MG5_aMC | Yes | Yes | No virt. | Yes | No | No |
| MoCaNLO+Recola | Yes | Yes | Yes | Yes | Yes | Yes |
| PHANTOM | Yes | Yes | Yes | No | - | - |
| VBFNLO | Yes | No | Yes | Yes | No | No |
| Whizard | Yes | Yes | Yes | No | - | - |

Table 1: Summary of the different properties of the codes employed in the comparison.

- The program MoCaNLO+Recola is made of a flexible Monte Carlo program dubbed MoCaNLO [43] and the general matrix element generator Recola [44, 45]. To numerically evaluate the one-loop scalar and tensor integrals, Recola relies on the Collier library [15, 16], These tools have been successfully used for the computation of NLO corrections for VBS [13, 12].

- VBFNLO [41, 42, 11] is a flexible parton-level Monte Carlo for processes with electroweak bosons. It allows the calculation of VBS processes at NLO QCD in the VBF approximation and including the s-channel triboson contribution, neglecting interferences between the two. Besides the SM, also anomalous couplings of the Higgs and gauge bosons can be simulated.

- Whizard [46, 47] is a multi-purpose event generator with the LO matrix element generator O'Mega. It provides FKS subtraction terms for any NLO process, while virtual matrix elements are provided externally by OpenLoops [32] (alternatively, Recola [44, 45] (cf. above) can be used as well). Whizard allows to simulate a huge number of BSM models as well, in particular for new physics in the VBS channel in terms of both higher-dimensional operators as well as explicit resonances.

NLO QCD corrections at fixed-order $\mathcal{O}(\alpha^6\alpha_s)$, for the process $\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$. In Tab. 1 the details of the various codes are reported. In particular, it is specified whether

- all $s$- and $t/u$-channel diagrams that lead to the considered final state are included;

- interferences between diagrams are included at LO;

- diagrams which do not feature two resonant vector bosons are included;

- the so-called non-factorisable (NF) QCD corrections, that is the corrections where (real or virtual) gluons are exchanged between different quark lines, are included;

- EW corrections to the $\mathcal{O}(\alpha^5\alpha_s)$ interference are included. These corrections are of the same order as the NLO QCD corrections to the $\mathcal{O}(\alpha^6)$ term.

### 3.3 Input parameters

We simulate VBS production at the LHC, with a center-of-mass energy $\sqrt{s} = 13\,\text{TeV}$. We assume five massless flavours in the proton, and employ the NNPDF 3.0 parton density [48] with NLO QCD evolution (the `lhaid` in LHAPDF6 [49] for this set is 260000) and strong coupling constant $\alpha_s(M_\mathrm{Z}) = 0.118$. Since the employed PDF set has no photonic density, photon-induced processes are not considered. Initial-state collinear singularity are factorised with the $\overline{\text{MS}}$ scheme, consistently with what is done in NNPDF.
We use the following values for the mass and width of the massive particles:

$$\begin{aligned}
m_\mathrm{t} &= 173.21\,\text{GeV}, & \Gamma_\mathrm{t} &= 0\,\text{GeV}, \\
M_\mathrm{Z}^\mathrm{OS} &= 91.1876\,\text{GeV}, & \Gamma_\mathrm{Z}^\mathrm{OS} &= 2.4952\,\text{GeV}, \\
M_\mathrm{W}^\mathrm{OS} &= 80.385\,\text{GeV}, & \Gamma_\mathrm{W}^\mathrm{OS} &= 2.085\,\text{GeV}, \\
M_\mathrm{H} &= 125.0\,\text{GeV}, & \Gamma_\mathrm{H} &= 4.07\times 10^{-3}\,\text{GeV},
\end{aligned} \tag{1}$$

and renormalise the EW coupling in the $G_\mu$ scheme [50] where

$$G_\mu = 1.16637 \times 10^{-5}\,\text{GeV}^{-2}. \tag{2}$$

The derived value of the EW coupling $\alpha$, corresponding to our choice of input parameters, is

$$\alpha = 7.555310522369 \times 10^{-3}. \tag{3}$$

We employ the complex-mass scheme [51, 52] to treat unstable intermediate particles in a gauge-invariant manner **CHECK THAT ALL CODES USE THE CMS**.

The renormalisation and factorisation scales are set dynamically as

$$\mu_\text{ren} = \mu_\text{fac} = \sqrt{p_{\mathrm{T,j_1}}\, p_{\mathrm{T,j_2}}}, \tag{4}$$

Cross sections and distribution are computed within the following VBS cuts inspired from experimental measurements [1–3, 53]:

- The two same-sign charged leptons are required to have

$$p_{\mathrm{T},\ell} > 20\,\text{GeV}, \qquad |y_\ell| < 2.5, \qquad \Delta R_{\ell\ell} > 0.3\,. \tag{5}$$

- The total missing transverse energy, computed from the vectorial sum of the transverse momenta of the two neutrinos in the event, is required to be

$$E_\text{T,miss} = p_\text{T,miss} > 40\,\text{GeV}\,. \tag{6}$$

- QCD partons (quark and gluons) are clustered together using the anti-$k_T$ algorithm [54] with distance parameter $R = 0.4$. Jets are required to have

$$p_\mathrm{T,j} > 30\,\text{GeV}, \qquad |y_\mathrm{j}| < 4.5, \qquad \Delta R_{\mathrm{j}\ell} > 0.3\,. \tag{7}$$

  On the two jets with largest transverse-momentum the following invariant-mass and rapidity-separation cuts are imposed

$$m_\mathrm{jj} > 500\,\text{GeV}, \qquad |\Delta y_\mathrm{jj}| > 2.5. \tag{8}$$

- When EW corrections are computed, real photons and charged fermion are clustered together using the anti-$k_T$ algorithm with radius parameter $R = 0.1$. In this case, leptons and quarks mentioned above must be understood as *dressed fermions*. Photons which are not combined at this step are clustered with QCD partons to form jets as it is described previously.

# 4 Leading-order study

## 4.1 Three contributions

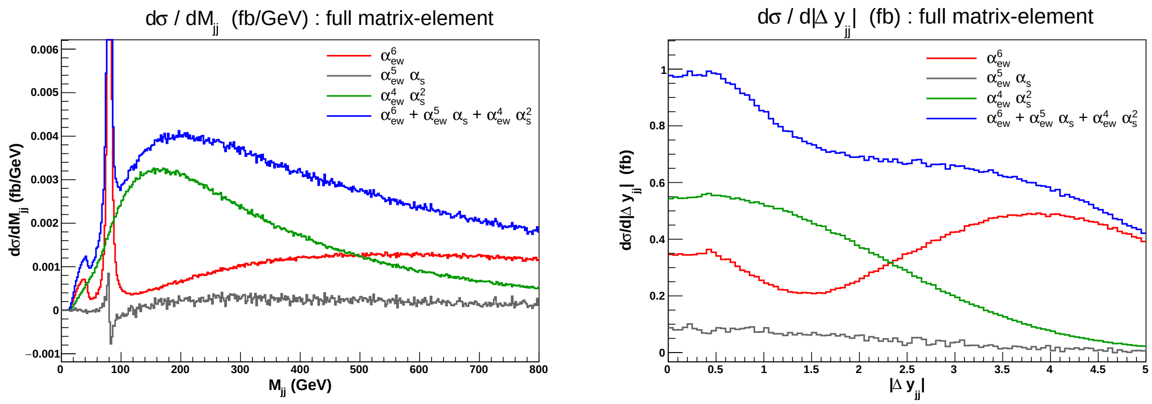


Figure 2: Differential distribution in the di-jet invariant mass (left) and the difference of the jet rapidity (right) at LO. No cuts on the di-jet invariant mass and the different of the jet rapidity are applied.

One can also see this in three different plots in the plan $(m_{\text{jj}}, \Delta y_{\text{jj}})$.

## 4.2 Inclusive comparison

## 4.3 Comparison in the fiducial region

In Tab. 2 we report the total rates at LO accuracy obtained with the set-up described above, and in Fig. 5 we show the results for the tagging-jet (left) and lepton-pair (right) invariant-mass distribution. In both case we show the absolute distributions in the main frame of the figures, while in the inset the ratio over VBFNLO is displayed. For both observables we find an excellent agreement among the various tools, which confirms the fact that contributions from $s-$channel diagrams as well as from non-resonant configurations are strongly suppressed in the fiducial region.

# 5 Next-to-leading order QCD

## 5.1 Inclusive comparision

Scan at NLO

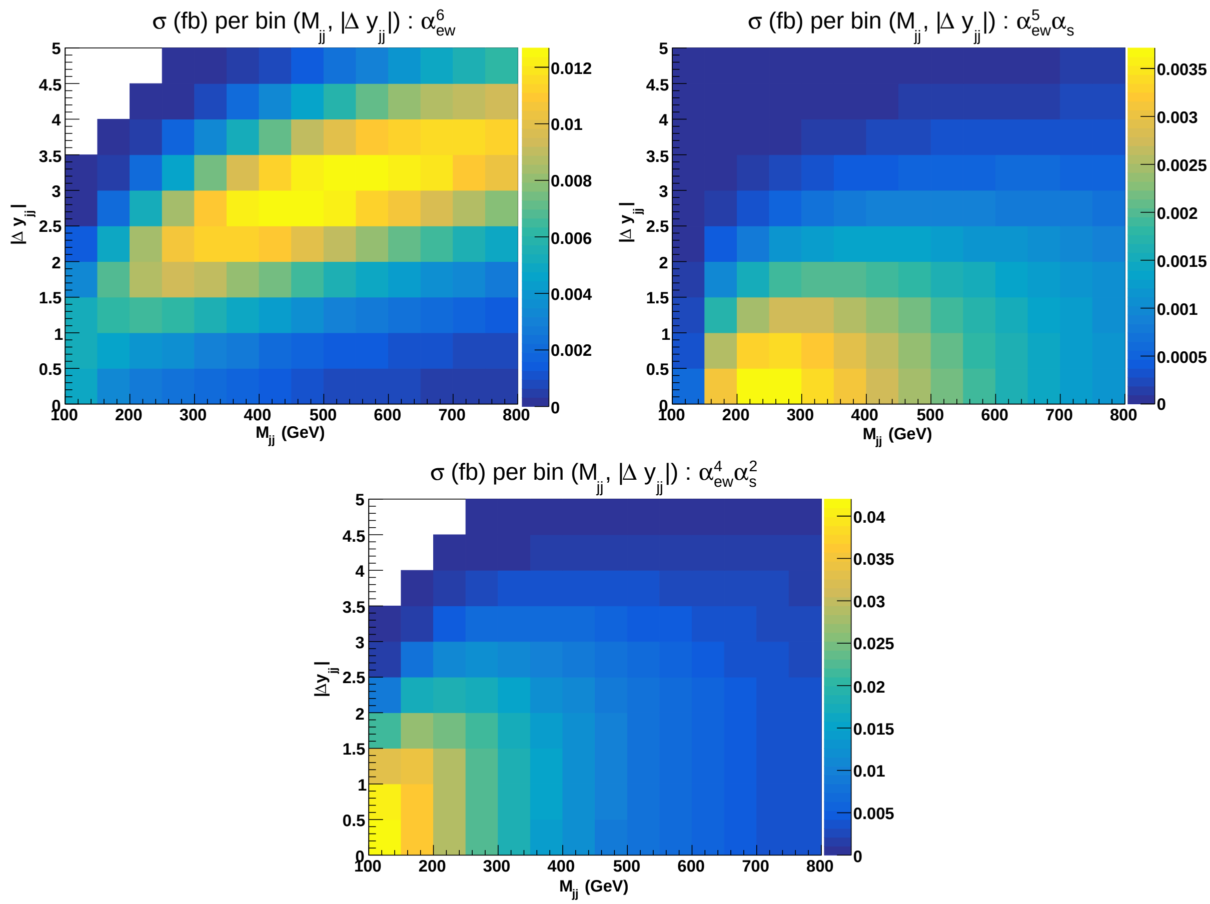


Figure 3: Cross sections (fb) per bin in the plan $(m_{\mathrm{jj}}, \Delta y_{\mathrm{jj}})$ for the three LO contributions of orders $\mathcal{O}(\alpha^6)$ (top left), $\mathcal{O}(\alpha^5\alpha_{\mathrm{s}})$ (top right), and $\mathcal{O}(\alpha^4\alpha_{\mathrm{s}}^2)$ (bottom).

| Code | $\sigma$[fb] |
|---|---|
| Bonsay | $X \pm 0.0002$ |
| MG5_aMC | $X \pm 0.001$ |
| MoCaNLO+Recola | $1.4347 \pm 0.0001$ |
| PHANTOM | $1.4374 \pm 0.0006$ |
| POWHEG | $1.44092 \pm 0.00009$ |
| VBFNLO | $1.43796 \pm 0.00005$ |
| Whizard | $1.4363 \pm 0.0009$ |

Table 2: Rates at LO accuracy within VBS cuts obtained with the different codes used in this comparison, for the $\mathrm{pp} \to \mu^+\nu_\mu\mathrm{e}^+\nu_{\mathrm{e}}\mathrm{jj}$ process.

### 5.2 Comparison in the fiducial region

Cross secitons at NLO

At NLO, rates show slightly larger discrepancies, as it can be observed in Tab. 4. This is most likely due to low dijet invariant-mass configurations, where $s-$channel diagrams and interferences are less suppressed than at LO, because of the presence of extra QCD radiation.

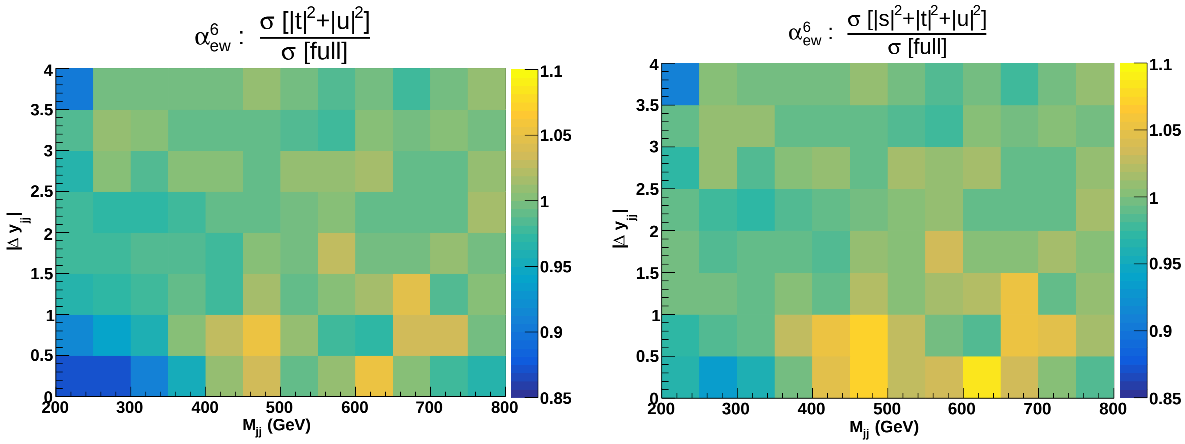


Figure 4: Cross sections (fb) per bin in the plan $(m_{\mathrm{jj}}, \Delta y_{\mathrm{jj}})$ at order $\mathcal{O}(\alpha^6)$. Ratio of approximated squared amplitudes over the full matrix element. The approximated squared amplitudes are computed as $|\mathcal{A}|^2 \sim |t|^2 + |u|^2$ (left) and $|\mathcal{A}|^2 \sim |s|^2 + |t|^2 + |u|^2$ (right).

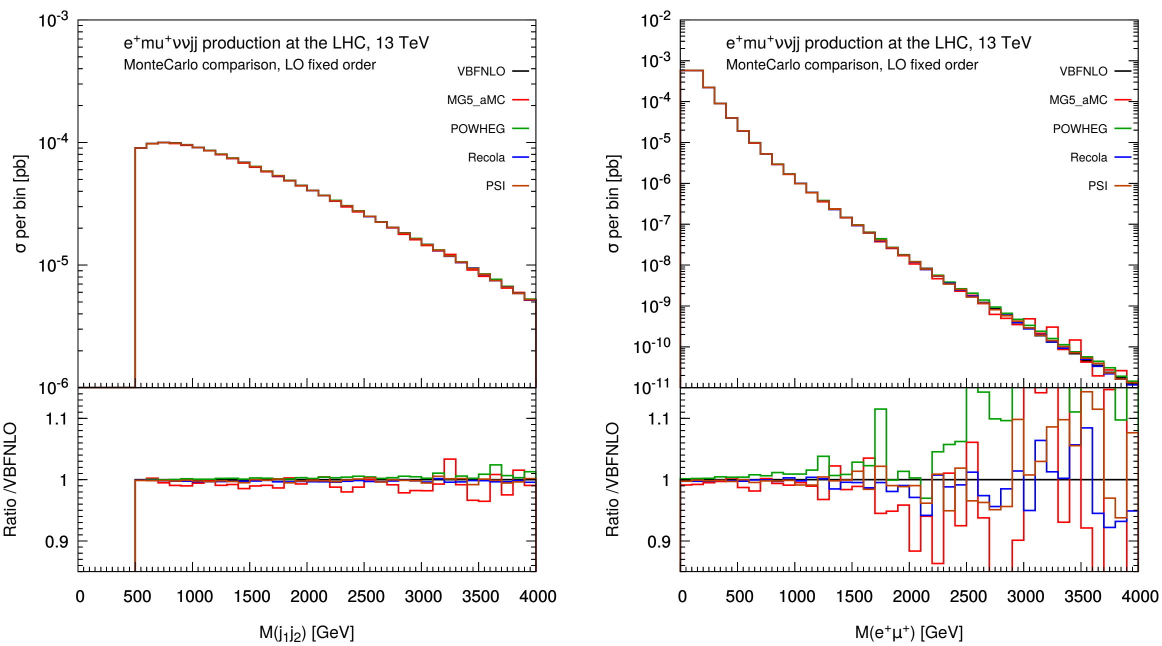


Figure 5: Invariant-mass of the two tagging jets (left) and of the two leptons (right), at LO accuracy, computed with the different codes used in this comparison. The inset shows the ratio over VBFNLO.

Distributions at NLO

FIGURE

Figure 6: Cross–section (fb) per bin of ($M_{jj}$, $\Delta y_{jj}$) at NLO QCD $\mathcal{O}(\alpha_{ew}^6 \alpha_s)$, without any cut on the $jj$ pair kinematics. Results of `XXX` calculations.

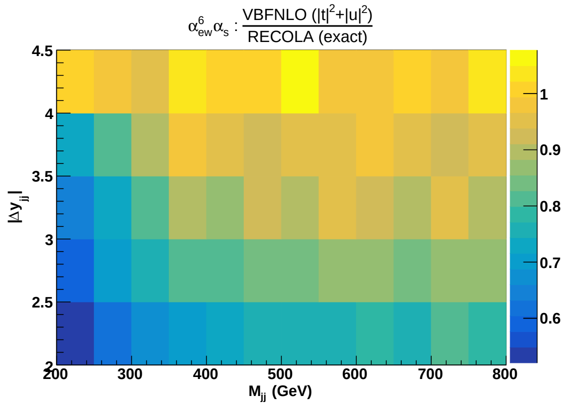


Figure 7: Cross–sections (fb) per bin of ($M_{jj}$, $\Delta y_{jj}$) at $\mathcal{O}(\alpha_{ew}^6 \alpha_s)$, without any cut on the $jj$ pair kinematics: ratio of approximated squared amplitudes over the full matrix element. The approximated squared amplitudes are computed as $|\mathcal{A}|^2 \sim |t|^2 + |u|^2$ (left) and $|\mathcal{A}|^2 \sim |s|^2 + |t|^2 + |u|^2$ (right). Results of `VBFNLO` (approximated) and `RECOLA` (full) calculations. RIGHT SIDE FIG. IN PREPARATION. QUESTION: is RECOLA calc. 'exact' ?

| Code | $\sigma$[fb] |
|---|---|
| BONSAY | $X \pm 0.0009$ |
| MG5_AMC | $X \pm 0.003$ |
| MOCANLO+RECOLA | $1.382 \pm 0.002$ |
| POWHEG | $1.3556 \pm 0.0009$ |
| VBFNLO | $1.3916 \pm 0.0001$ |

Table 3: Rates at NLO-QCD accuracy within VBS cuts obtained with the different codes used in this comparison, for the pp $\to \mu^+\nu_\mu e^+\nu_e jj$ process.

| Code | $\sigma$[fb] |
|---|---|
| MG5_AMC | $X \pm 0.003$ |
| POWHEG | $1.3633 \pm 0.0004$ |
| VBFNLO | $X \pm 0.0003$ |

Table 4: Rates at NLO-QCD accuracy matched to parton shower within VBS cuts obtained with the different codes used in this comparison, for the pp $\to \mu^+\nu_\mu e^+\nu_e jj$ process.

# 6 Matching to parton shower

# 7 Conclusion

- Sum-up of the study.

[MP: This might deserve a section on its own.]

Recommendations to experimental collaborations:
- Combinations with EW NLO corrections.
- Missing higher EW order: $\pm\delta^2_{\mathrm{NLOEW}}$
- Systematics when using NLO QCD approximation
- Systematics of different parton shower
- Combined measurement including EW, QCD, and interference
- Move to NLO predictions / generators
- Comment on the irreducible QCD background

## Acknowledgements

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# A Appendix one

## References

[1] **ATLAS** Collaboration, G. Aad *et al.*, *Evidence for Electroweak Production of $W^\pm W^\pm jj$ in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector*. Phys. Rev. Lett. **113** (2014) no. 14, 141803, `arXiv:1405.6241 [hep-ex]`.

[2] **ATLAS** Collaboration, M. Aaboud *et al.*, *Measurement of $W^\pm W^\pm$ vector-boson scattering and limits on anomalous quartic gauge couplings with the ATLAS detector*. Phys. Rev. **D96** (2017) 012007, `arXiv:1611.02428 [hep-ex]`.

[3] **CMS** Collaboration, V. Khachatryan *et al.*, *Study of vector boson scattering and search for new physics in events with two same-sign leptons and two jets*. Phys. Rev. Lett. **114** (2015) no. 5, 051801, `arXiv:1410.6315 [hep-ex]`.

[4] B. Jäger, 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. **D80** (2009) 034022, `arXiv:0907.0580 [hep-ph]`.

[5] B. Jäger and G. Zanderighi, *NLO corrections to electroweak and QCD production of $W^+W^+$ plus two jets in the POWHEGBOX*. JHEP **11** (2011) 055, `arXiv:1108.0864 [hep-ph]`.

[6] A. Denner, L. Hošeková, and S. Kallweit, *NLO QCD corrections to $W^+W^+jj$ production in vector-boson fusion at the LHC*. Phys. Rev. **D86** (2012) 114014, `arXiv:1209.2389 [hep-ph]`.

[7] M. Rauch, *Vector-Boson Fusion and Vector-Boson Scattering*. `arXiv:1610.08420 [hep-ph]`.

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

[9] T. Melia, P. Nason, R. Röntsch, and G. Zanderighi, *$W^+W^+$ plus dijet production in the POWHEGBOX*. Eur. Phys. J. **C71** (2011) 1670, `arXiv:1102.4846 [hep-ph]`.

[10] 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. **D89** (2014) no. 5, 054009, `arXiv:1311.6738 [hep-ph]`.

[11] J. Baglio *et al.*, *Release Note - VBFNLO 2.7.0*. `arXiv:1404.3940 [hep-ph]`.

[12] B. Biedermann, A. Denner, and M. Pellen, *Complete NLO corrections to* $\mathrm{W^+W^+}$ *scattering and its irreducible background at the LHC*. `arXiv:1708.00268 [hep-ph]`.

[13] B. Biedermann, A. Denner, and M. Pellen, *Large electroweak corrections to vector-boson scattering at the Large Hadron Collider*. Phys. Rev. Lett. **118** (2017) no. 26, 261801, `arXiv:1611.02951 [hep-ph]`.

[14] S. Dittmaier and M. Roth, *LUSIFER: A LUcid approach to six FERmion production*. Nucl. Phys. **B642** (2002) 307–343, `arXiv:hep-ph/0206070 [hep-ph]`.

[15] A. Denner, S. Dittmaier, and L. Hofer, *COLLIER - A fortran-library for one-loop integrals*. PoS **LL2014** (2014) 071, `arXiv:1407.0087 [hep-ph]`.

[16] A. Denner, S. Dittmaier, and L. Hofer, COLLIER*: a fortran-based Complex One-Loop LIbrary in Extended Regularizations*. Comput. Phys. Commun. **212** (2017) 220–238, `arXiv:1604.06792 [hep-ph]`.

[17] J. Alwall *et al.*, *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*. JHEP **07** (2014) 079, `arXiv:1405.0301 [hep-ph]`.

[18] S. Frixione, Z. Kunszt, and A. Signer, *Three jet cross-sections to next-to-leading order*. Nucl. Phys. **B467** (1996) 399–442, `arXiv:hep-ph/9512328 [hep-ph]`.

[19] S. Frixione, *A General approach to jet cross-sections in QCD*. Nucl. Phys. **B507** (1997) 295–314, `arXiv:hep-ph/9706545 [hep-ph]`.

[20] R. Frederix, S. Frixione, F. Maltoni, and T. Stelzer, *Automation of next-to-leading order computations in QCD: The FKS subtraction*. JHEP **10** (2009) 003, `arXiv:0908.4272 [hep-ph]`.

[21] R. Frederix, S. Frixione, A. S. Papanastasiou, S. Prestel, and P. Torrielli, *Off-shell single-top production at NLO matched to parton showers*. JHEP **06** (2016) 027, `arXiv:1603.01178 [hep-ph]`.

[22] G. Ossola, C. G. Papadopoulos, and R. Pittau, *Reducing full one-loop amplitudes to scalar integrals at the integrand level*. Nucl. Phys. **B763** (2007) 147–169, `arXiv:hep-ph/0609007 [hep-ph]`.

[23] P. Mastrolia, E. Mirabella, and T. Peraro, *Integrand reduction of one-loop scattering amplitudes through Laurent series expansion*. JHEP **06** (2012) 095, `arXiv:1203.0291 [hep-ph]`. [Erratum: JHEP11,128(2012)].

[24] G. Passarino and M. J. G. Veltman, *One-loop corrections for $e^+e^-$ annihilation into $\mu^+\mu^-$ in the Weinberg model*. Nucl. Phys. **B160** (1979) 151–207.

[25] A. I. Davydychev, *A Simple formula for reducing Feynman diagrams to scalar integrals*. Phys. Lett. **B263** (1991) 107–111.

[26] A. Denner and S. Dittmaier, *Reduction schemes for one-loop tensor integrals*. Nucl. Phys. **B734** (2006) 62–115, `hep-ph/0509141`.

[27] V. Hirschi, R. Frederix, S. Frixione, M. V. Garzelli, F. Maltoni, and R. Pittau, *Automation of one-loop QCD corrections*. JHEP **05** (2011) 044, `arXiv:1103.0621 [hep-ph]`.

[28] G. Ossola, C. G. Papadopoulos, and R. Pittau, *CutTools: A Program implementing the OPP reduction method to compute one-loop amplitudes*. JHEP **03** (2008) 042, `arXiv:0711.3596 [hep-ph]`.

[29] T. Peraro, *Ninja: Automated Integrand Reduction via Laurent Expansion for One-Loop Amplitudes*. Comput. Phys. Commun. **185** (2014) 2771–2797, `arXiv:1403.1229 [hep-ph]`.

[30] V. Hirschi and T. Peraro, *Tensor integrand reduction via Laurent expansion*. JHEP **06** (2016) 060, `arXiv:1604.01363 [hep-ph]`.

[31] H.-S. Shao, *Iregi user manual, unpublished*.

[32] F. Cascioli, P. Maierhofer, and S. Pozzorini, *Scattering Amplitudes with Open Loops*. Phys. Rev. Lett. **108** (2012) 111601, `arXiv:1111.5206 [hep-ph]`.

[33] A. Ballestrero, A. Belhouari, G. Bevilacqua, V. Kashkan, and E. Maina, *PHANTOM: A Monte Carlo event generator for six parton final states at high energy colliders*. Comput. Phys. Commun. **180** (2009) 401–417, `arXiv:0801.3359 [hep-ph]`.

[34] A. Denner and S. Dittmaier, *The Complex-mass scheme for perturbative calculations with unstable particles*. Nucl. Phys. Proc. Suppl. **160** (2006) 22–26, `arXiv:hep-ph/0605312 [hep-ph]`. [,22(2006)].

[35] A. Ballestrero, "PHACT: Helicity amplitudes for present and future colliders," in *High energy physics and quantum field theory. Proceedings, 14th International Workshop, QFTHEP'99, Moscow, Russia, May 27-June 2, 1999*, pp. 303–309. 1999. `arXiv:hep-ph/9911318 [hep-ph]`.

[36] A. Ballestrero and E. Maina, *A New method for helicity calculations*. Phys. Lett. **B350** (1995) 225–233, `arXiv:hep-ph/9403244 [hep-ph]`.

[37] F. Berends, P. Daverveldt, and R. Kleiss, *Complete lowest-order calculations for four-lepton final states in electron-positron collisions*. Nuclear Physics B **253** (1985) no. Supplement C, 441 – 463. `http://www.sciencedirect.com/science/article/pii/0550321385905413`.

[38] G. P. Lepage, *A new algorithm for adaptive multidimensional integration*. Journal of Computational Physics **27** (1978) no. 2, 192 – 203. `http://www.sciencedirect.com/science/article/pii/0021999178900049`.

[39] 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, `arXiv:1002.2581 [hep-ph]`.

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

[41] K. Arnold *et al.*, *VBFNLO: A Parton level Monte Carlo for processes with electroweak bosons*. Comput. Phys. Commun. **180** (2009) 1661–1670, `arXiv:0811.4559 [hep-ph]`.

[42] K. Arnold *et al.*, *VBFNLO: A Parton Level Monte Carlo for Processes with Electroweak Bosons – Manual for Version 2.5.0*. `arXiv:1107.4038 [hep-ph]`.

[43] R. Feger, "MoCaNLO: a generic Monte Carlo event generator for NLO calculations of hadron-collider processes." unpublished, 2015.

[44] S. Actis *et al.*, *Recursive generation of one-loop amplitudes in the Standard Model*. JHEP **04** (2013) 037, `arXiv:1211.6316 [hep-ph]`.

[45] S. Actis *et al.*, *RECOLA: REcursive Computation of One-Loop Amplitudes*. Comput. Phys. Commun. **214** (2017) 140–173, `arXiv:1605.01090 [hep-ph]`.

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

[47] 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]`.

[48] **NNPDF** Collaboration, R. D. Ball *et al.*, *Parton distributions for the LHC Run II*. JHEP **04** (2015) 040, `arXiv:1410.8849 [hep-ph]`.

[49] A. Buckley, J. Ferrando, S. Lloyd, K. Nordström, B. Page, M. Rüfenacht, M. Schönherr, and G. Watt, *LHAPDF6: parton density access in the LHC precision era*. Eur. Phys. J. **C75** (2015) 132, `arXiv:1412.7420 [hep-ph]`.

[50] A. Denner, S. Dittmaier, M. Roth, and D. Wackeroth, *Electroweak radiative corrections to $e^+e^- \to WW \to 4$ fermions in double-pole approximation: The RACOONWW approach*. Nucl. Phys. **B587** (2000) 67–117, `arXiv:hep-ph/0006307 [hep-ph]`.

[51] A. Denner *et al.*, *Predictions for all processes $e^+e^- \to 4$ fermions $+\gamma$*. Nucl. Phys. **B560** (1999) 33–65, `arXiv:hep-ph/9904472`.

[52] A. Denner *et al.*, *Electroweak corrections to charged-current $e^+e^- \to 4$ fermion processes: Technical details and further results*. Nucl. Phys. **B724** (2005) 247–294, `arXiv:hep-ph/0505042`.

[53] **CMS** Collaboration, *Observation of electroweak production of same-sign W boson pairs in the two jet and two same-sign lepton final state in proton-proton collisions at 13 TeV*. CMS-PAS-SMP-17-004.

[54] M. Cacciari, G. P. Salam, and G. Soyez, *The anti-$k_t$ jet clustering algorithm*. JHEP **04** (2008) 063, `arXiv:0802.1189 [hep-ph]`.