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

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Abstract

Abstract to be written here.

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1 Introduction

The measurements are [1–3].

In the last decade many codes capable of performing VBS simulations have appeared. Within a network such as VBSCan it is therefore natural to perform a quantitative comparison of these codes, both to cross-validate the results and to assess the impact of the different approximations which are used. In fact, already at LO, when considering the process $\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ at order $\mathcal{O}(\alpha^6)$, the various implementations VBS simulations are different. They differ, for example by the (non-)inclusion of diagrams with vector bosons in the s-channel or by the treatment of interferences between diagrams. The reason of these differences is that, when typical signal cuts for VBS are imposed, these effects turn to be small on rates and distributions.

2 Definition of the process

3 Details of the calculations

3.1 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 [4] 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 [5, 6].

- MadGraph5_aMC@NLO [7] 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 [8, 9] (automated in the module MadFKS [10, 11]) for regulating IR singularities. The computationsof one-loop amplitudes are carried out by switching dynamically between two integral-reduction techniques, OPP [12] or Laurent-series expansion [13], and TIR [14–16]. These have been automated in the module MadLoop [17], which in turn exploits CutTools [18], Ninja [19, 20], or IREGI [21], together with an in-house implementation of the OpenLoops optimisation [22].
  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

[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.

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.

- PHANTOM [23] is a dedicated tree–level Monte Carlo for six parton final states at pp, $p\bar{p}$ and e^+e^- colliders at α_{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 [24] computed via the modular helicity formalism [25, 26]. The integration uses a multichannel approach [27] and an adaptive strategy [28]. PHANTOM generates unweighted events at parton–level for both the SM and a few instances of BSM theories..

- The POWHEG-BOX [29, 30] 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 [8] 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 [31–33] 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.]

- The program RECOLA+MOCANLO is made of a flexible Monte Carlo program dubbed MOCANLO [34] and the general matrix element generator RECOLA [35, 36]. To numerically evaluate the one-loop scalar and tensor integrals, RECOLA relies on the COLLIER library [5, 6], These tools have been successfully used for the computation of NLO corrections for VBS [37, 38].

- VBFNLO [31–33] 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 [39, 40] 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 [22] (alternatively, RECOLA [35, 36] (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.

The complete comparison of the codes will be published in a separate work. Here, we present some preliminary results obtained at LO ($\mathcal{O}(\alpha^6)$) and including 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-factorizable (NF) QCD corrections, that is the corrections where (real or virtual) gluons are exchanged between different quark lines, are included;

Contact person	Code	$\mathcal{O}(\alpha^6)$ $\lvert s\rvert^2/\lvert t\rvert^2/\lvert u\rvert^2$	$\mathcal{O}(\alpha^6)$ interf.	Non-res.	NF QCD	EW corr. to $\mathcal{O}(\alpha^5\alpha_s)$
A. Karlberg	POWHEG	t/u	No	Yes	No	No
M. Pellen	Recola+MoCaNLO	Yes	Yes	Yes	Yes	Yes
M. Rauch	VBFNLO	Yes	No	Yes	No	No
C. Schwan	Bonsay	t/u	No	Yes, virt. No	No	No
M. Zaro	MG5_aMC	Yes	Yes	No virt.	No	No
V. Rothe	Whizard	Yes	Yes	Yes	Yes	Yes

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

- 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.

3.2 Input parameters

We simulate VBS production at the LHC, with a center-of-mass energy $\sqrt{s} = 13\,\mathrm{TeV}$. We assume five massless flavours in the proton, and employ the NNPDF 3.0 parton density [41] with NLO QCD evolution (the `lhaid` in LHAPDF6 [42] 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 $\overline{\mathrm{MS}}$ scheme, consistently with what is done in NNPDF.
We use the following values for the mass and width of the massive particles:

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

and renormalise the EW coupling in the G_μ scheme [43] where

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

The derived value of the EW coupling α, corresponding to our choice of input parameters, is

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

We employ the complex-mass scheme [44, 45] to treat unstable intermediate particles in a gauge-invariant manner **CHECK THAT ALL CODES USE THE CMS**.

Cross sections and distribution are computed within the following VBS cuts inspired from experimental measurements [1–3, 46]:

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

$$p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}, \qquad |y_\ell| < 2.5, \qquad \Delta R_{\ell\ell} > 0.3\,. \tag{4}$$

- 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

$$E_{\mathrm{T,miss}} = p_{\mathrm{T,miss}} > 40\,\mathrm{GeV}\,. \tag{5}$$

- QCD partons (quark and gluons) are clustered together using the anti-k_T algorithm [47] with distance parameter $R = 0.4$. Jets are required to have

$$p_{\mathrm{T,j}} > 30\,\mathrm{GeV}, \qquad |y_{\mathrm{j}}| < 4.5, \qquad \Delta R_{\mathrm{j}\ell} > 0.3\,. \tag{6}$$

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

$$m_{\mathrm{jj}} > 500\,\mathrm{GeV}, \qquad |\Delta y_{\mathrm{jj}}| > 2.5. \tag{7}$$

- 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 Fixed order comparisons

4.1 Cross sections

In Tab. 2 we report the total rates at LO accuracy obtained with the set-up described above, and in Fig. 1 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.

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

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.

Code	σ[fb]
BONSAY	$X \pm 0.0009$
MG5_aMC	$X \pm 0.003$
MoCaNLO+Recola	1.382 ± 0.002
POWHEG	1.3556 ± 0.0009
VBFNLO	1.3916 ± 0.0001

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

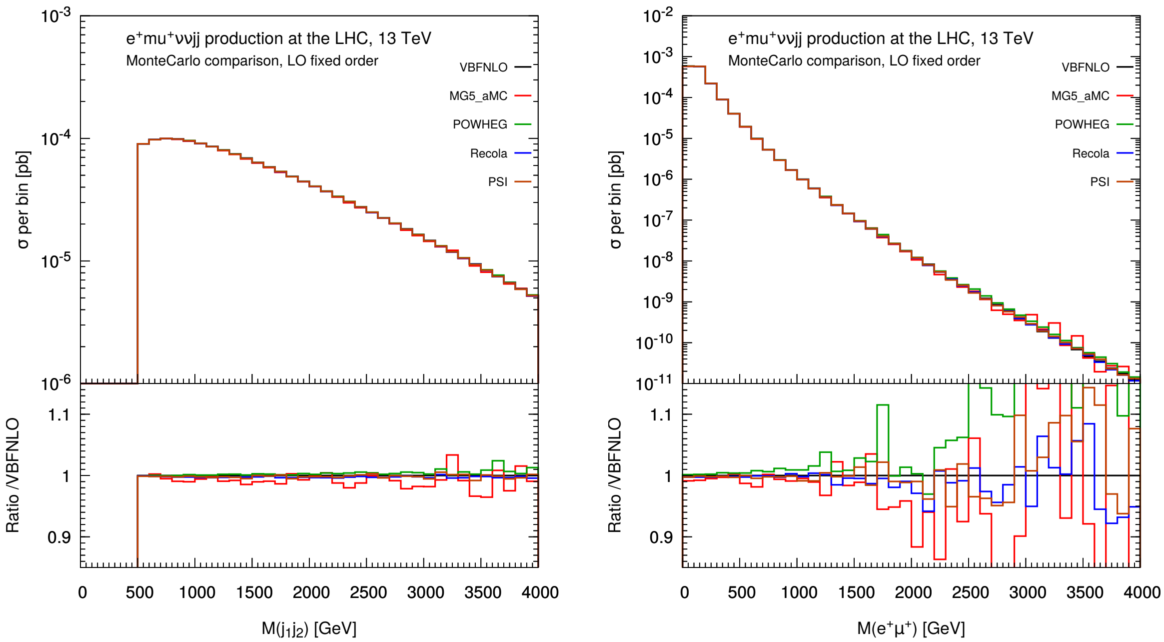

Figure 1: Invariant-mass of the two tagging jets (left) and of the two leptons (right), at LO accuracy, computed with the different codes used in this comparison. The inset shows the ratio over VBFNLO.

4.2 Differential distributions

5 Influence of the fiducial region

6 Matching to parton shower

7 Conclusion

Acknowledgements

We thank ... Acknowledgement of VBSCAN COST action.

Code	σ[fb]
MG5_aMC	$X \pm 0.003$
POWHEG	1.3633 ± 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 $\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ process.

A Appendix one

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