

Monte Carlo comparisons  
VBSCAN Cost Action

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October 17, 2017

## **Abstract**

# Part I

## Introduction

## Part II

$$pp \rightarrow \mu^+ \nu_\mu e^+ \nu_e jj$$

## 0.1 Input parameters

- Centre-of-mass energy of 13 TeV at the LHC.
- Parton distribution function (PDF): NNPDF-3.0 at NLO with  $\alpha_s(M_Z) = 0.118$  (we use it at both LO and NLO). The LHAPDF ID for this set is 260000.
- Flavour scheme: fixed  $N_F = 5$  flavour scheme (no bottom quark appear in the final or initial state). This means that the bottom quark is considered massless.
- Photon induced are neglected (for now).
- Renormalisation scheme: complex-mass scheme if possible. If other schemes are used, we have to estimate the possible differences.
- Factorisation scheme:  $\overline{\text{MS}}$  as for NNPDF.
- Scales: factorisation and renormalisation scale, [MP:  $\mu_R = \mu_F = \mu$ .

$$\mu = \sqrt{p_{T,j1} p_{T,j2}}, \quad (1)$$

where the jets are the tagging jets.]

- $\alpha$ :  $G_\mu$  scheme with:

$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \left( 1 - \frac{M_W^2}{M_Z^2} \right) \quad \text{with} \quad G_\mu = 1.16637 \times 10^{-5} \text{ GeV}. \quad (2)$$

The numerical value is:  $\alpha = 7.555310522369 \times 10^{-3}$ .

- Mass and width of the massive particles:

$$\begin{aligned} m_t &= 173.21 \text{ GeV}, & \Gamma_t &= 0 \text{ GeV}, \\ M_Z^{\text{OS}} &= 91.1876 \text{ GeV}, & \Gamma_Z^{\text{OS}} &= 2.4952 \text{ GeV}, \\ M_W^{\text{OS}} &= 80.385 \text{ GeV}, & \Gamma_W^{\text{OS}} &= 2.085 \text{ GeV}, \\ M_H &= 125.0 \text{ GeV}, & \Gamma_H &= 4.07 \times 10^{-3} \text{ GeV}. \end{aligned} \quad (3)$$

The pole masses and widths entering the calculation are expressed in terms of the measured on-shell (OS) values for the W and Z bosons according to

$$M_V = M_V^{\text{OS}} / \sqrt{1 + (\Gamma_V^{\text{OS}} / M_V^{\text{OS}})^2}, \quad \Gamma_V = \Gamma_V^{\text{OS}} / \sqrt{1 + (\Gamma_V^{\text{OS}} / M_V^{\text{OS}})^2}. \quad (4)$$

Hence the numerical values are

$$\begin{aligned} M_Z &= 91.1534806191827 \text{ GeV}, & \Gamma_Z &= 2.494266378772824 \text{ GeV}, \\ M_W &= 80.3579736098775 \text{ GeV}, & \Gamma_W &= 2.084298998278219 \text{ GeV}. \end{aligned} \quad (5)$$

- Experimental signature: two equally charged leptons, missing transverse energy and at least two jets.
- Clustering: QCD partons are clustered into jets using the anti- $k_T$  algorithm with jet-resolution parameter  $R = 0.4$ . Photons from real radiation are recombined with the final-state quarks into jets or with the charged leptons into dressed leptons, in both cases via the anti- $k_T$  algorithm and a resolution parameter  $R = 0.1$  (this applies only when computing the EW corrections).
- Rapidity definition:  $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$  where  $E$  is the energy of the parton and  $p_z$  the component of its momentum along the beam axis.
- Distance definition:

$$\Delta R_{ij} = \sqrt{(\Delta\phi_{ij})^2 + (\Delta y_{ij})^2}, \quad (6)$$

Contact person	Code	$\mathcal{O}(\alpha^6)$ $ s ^2/ t ^2/ u ^2$	$\mathcal{O}(\alpha^6)$ interf.	Off-shell	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	Yes	No	No

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

with

$$\Delta\phi_{ij} = \begin{cases} |\phi_i - \phi_j| & \text{if } |\phi_i - \phi_j| < \pi \\ 2\pi - |\phi_i - \phi_j| & \text{else} \end{cases} \quad (7)$$

being the positive azimuthal-angle difference and  $\Delta y_{ij} = |y_i - y_j|$  being the positive rapidity difference.

- Definition of the missing transverse energy: transverse momentum of the sum of the two neutrinos momenta.

- Cuts on the leptons:

$$p_{T,\ell} > 20 \text{ GeV}, \quad |y_\ell| < 2.5, \quad \Delta R_{\ell\ell} > 0.3. \quad (8)$$

- Missing energy cut:

$$E_{T,\text{miss}} = p_{T,\text{miss}} > 40 \text{ GeV} \quad (9)$$

- Jet definition:

$$p_{T,j} > 30 \text{ GeV}, \quad |y_j| < 4.5, \quad \Delta R_{j\ell} > 0.3. \quad (10)$$

- Out of these 2/3 jets, the two hardest in pT (these are the tagging jets) are required to have:

$$m_{jj} > 500 \text{ GeV}, \quad |\Delta y_{jj}| > 2.5. \quad (11)$$

[MP: Now the  $\Delta R_{j\ell}$  cut is simply in the jet definition, it is not a requirement to be fulfilled by all the jets as before.]

## 0.2 Codes

### 0.2.1 POWHEG: Alexander Karlberg

VBF approximation?

### 0.2.2 VBFNLO: Michael Rauch

VBF approximation

### 0.2.3 WHIZARD: Simon Brass, Jürgen Reuter, Pascal Stienemeier

Full matrix element

### 0.2.4 RECOLA +MoCANLO: Mathieu Pellen

Full matrix element

### 0.2.5 MADGRAPH5\_AMC@NLO: Marco Zaro

To be checked what is possible

### 0.2.6 BONSAI: Christopher Schwan

## 0.3 Observables

- Cross section within cuts.
- Distribution in the number of jets.
- Invariant mass of the two hardest jets (two tagged jets).  
[0; 4 TeV] with bins of size 100 GeV (40 bins).
- $p_{T,j_1,j_2,j_3}$  and  $y_{j_1,j_2,j_3}$  of the two tagged jets [MP: and also the third jet at NLO] (not their sum)  
 $p_{T,j_1,j_2}$ : [0; 1 TeV] with bins of size 25 GeV (40 bins).  
 $y_{j_1,j_2}$ : [-5; 5] with bins of size 0.5 (20 bins).
- Invariant mass of the two charged leptons.  
[0; 4 TeV] with bins of size 100 GeV (40 bins).
- Zeppenfeld variable for  $\mu^+$  and  $e^+$ :  
 $z_\ell^* = |y_\ell - (y_{j_1} + y_{j_2})/2|/|\Delta y_{jj}|$   
[0; 1.5] with bins of size 0.05 (30 bins).
- $|\Delta y_{jj}|$ : [-5; 5] with bins of size 0.5 (20 bins).

## 0.4 Numerical results

### 0.4.1 LO $\mathcal{O}(\alpha^6)$

Code	$\sigma[\text{fb}]$
POWHEG	$1.5573 \pm 0.0003$
RECOLA +MoCANLO	$1.5503 \pm 0.0003$
VBFNLO	$1.5540 \pm 0.0002$
BONSAI	$1.5524 \pm 0.0002$
WHIZARD	$1.5539 \pm 0.0004$
MG5_AMC	$1.547 \pm 0.001$

Table 2: LO rates within VBS cuts from the different codes.

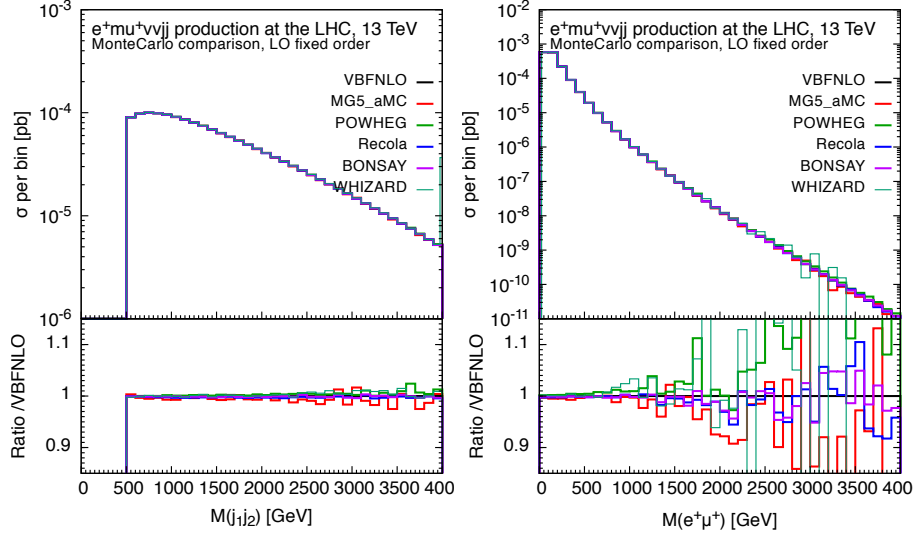


Figure 1: Invariant-mass of the two tagging jets (left) and of the two leptons (right), at LO.

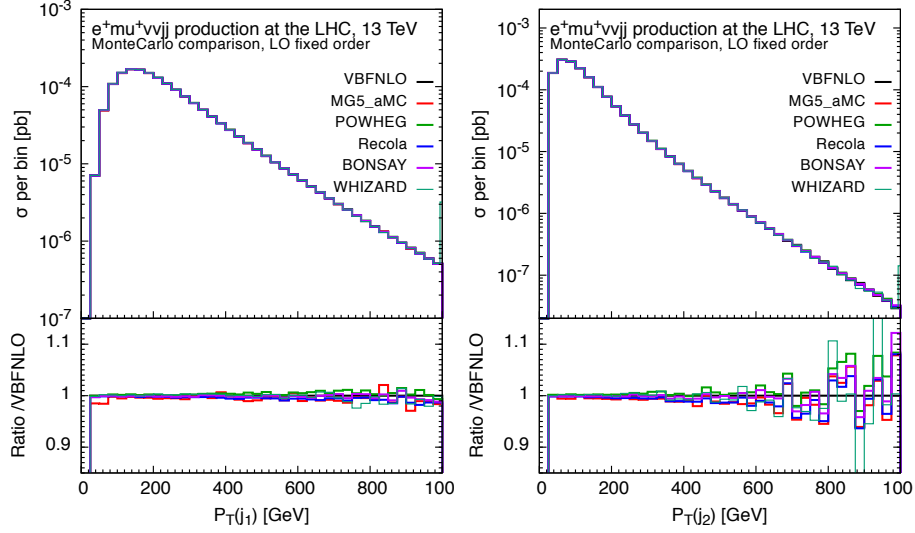


Figure 2: Transverse momentum of the first (left) and second (right) tagging jet, at LO.

#### 0.4.2 NLO $\mathcal{O}(\alpha^6\alpha_s)$

### 0.5 Plan

The plan is:

- Scan in  $m_{jj}$  and  $|\Delta y_{jj}|$  at LO and compute the EW, QCD and interference (for the one who can) contribution.



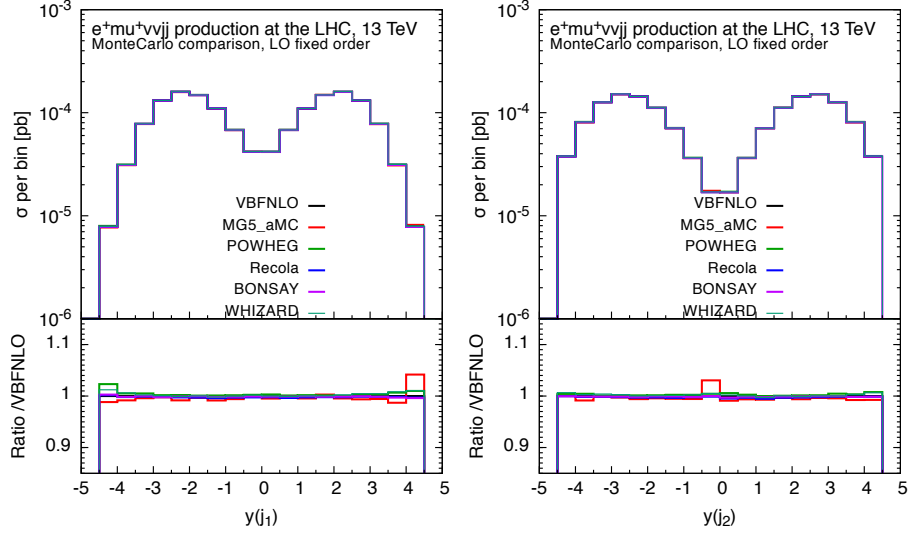


Figure 3: Rapidity of the first (left) and second (right) tagging jet, at LO.

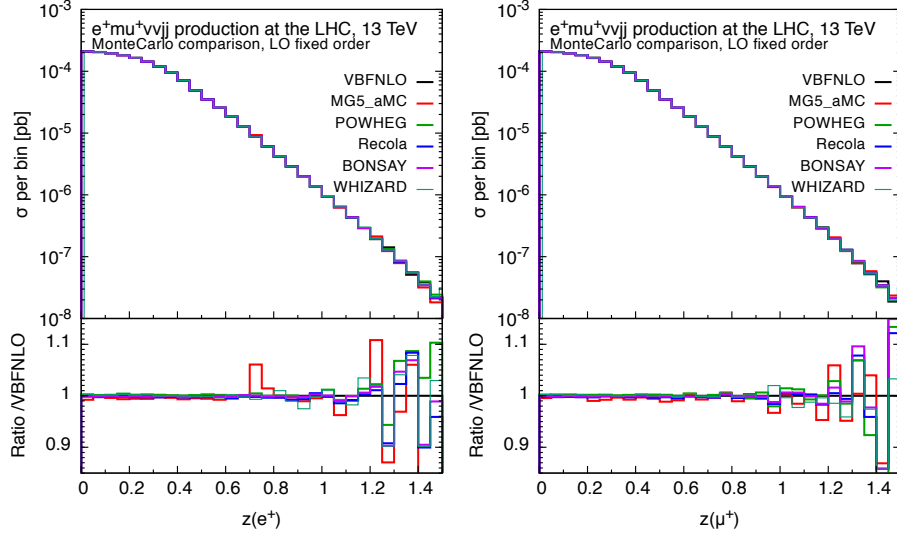


Figure 4: Zeppenfeld variable of the positron (left) and of the muon (right), at LO.

The binning in  $m_{jj}$  is  $[0, 50, 100, \dots, 450, 500, 600, 700, 800]$ .

The binning in  $|\Delta y_{jj}|$  is  $[0, 0.5, 1.0, 1.5, \dots, 4.5, 5.0]$ .

- Based on this, define a “control region” and a “signal region” (should be the one we have identified already). - Compute the QCD correction to QCD-induced and EW in these two regions. - Add PS to these computations (for those who can). - Add EW on top (probably only Mathieu).

Code	$\sigma[\text{fb}]$	$\sigma(n_j = 2)[\text{fb}]$	$\sigma(n_j = 3)[\text{fb}]$
POWHEG	$1.334 \pm 0.0003$	$0.808 \pm 0.001$	$0.5260 \pm 0.0005$
RECOLA + MoCANLO	$1.317 \pm 0.004$		
VBFNLO	$1.3664 \pm 0.0003$	$0.8394 \pm 0.0003$	$0.5270 \pm 0.00012$
BONSAY	$1.3469 \pm 0.0008$	$0.8303 \pm 0.0008$	$0.51662 \pm 0.00008$
MG5_aMC	$1.318 \pm 0.003$	$0.781 \pm 0.004$	$0.5374 \pm 0.0016$

Table 3: NLO rates within VBS cuts from the different codes.

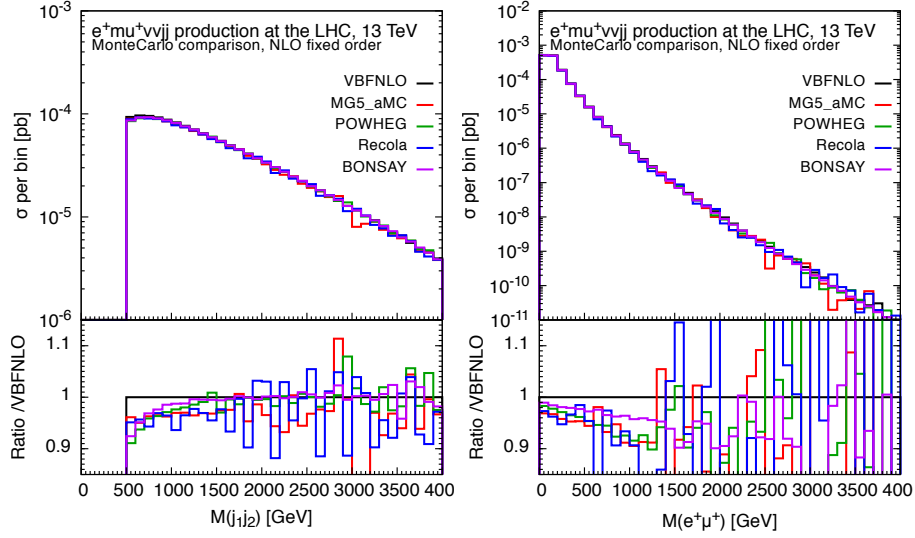


Figure 5: Invariant-mass of the two tagging jets (left) and of the two leptons (right), at NLO.

## 0.6 Remarks

- [MP: Do we want to keep the cuts as they are or do we want to update to the recommendation of WG2?]
- [MP: In particular we should write the report/article as we go further in the project in order to save time.]

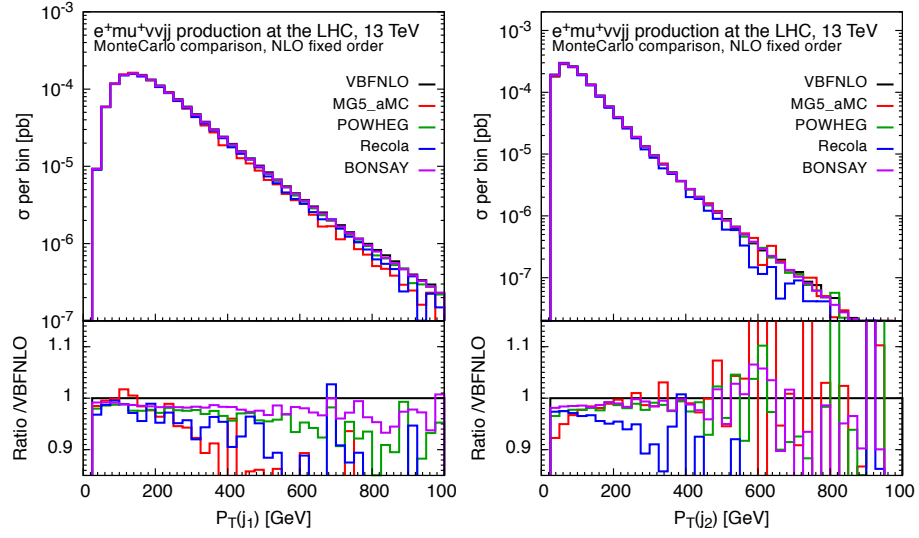


Figure 6: Transverse momentum of the first (left) and second (right) tagging jet, at NLO.

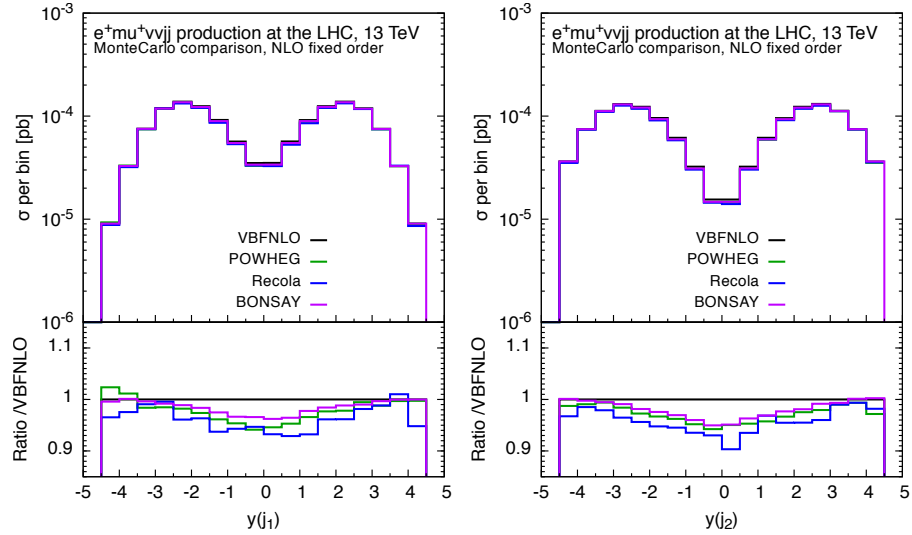


Figure 7: Rapidity of the first (left) and second (right) tagging jet, at NLO.

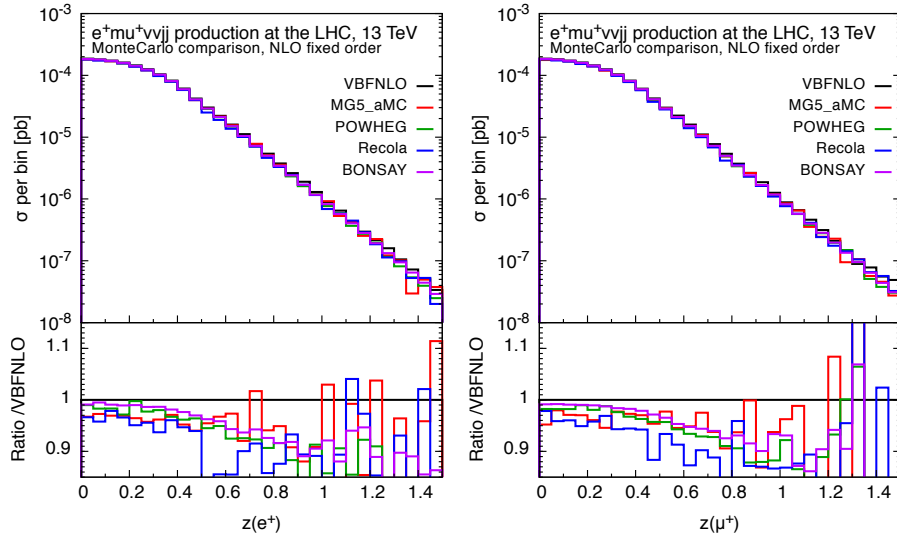


Figure 8: Zeppenfeld variable of the positron (left) and of the muon (right), at NLO.

## Part III

# Conclusion

## Part IV

# Acknowledgments

Karlsruhe for hosting the documents used for the comparison.