Monte Carlo comparisons VBSCAN Cost Action

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Abstract

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Introduction

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$\mathbf{pp} \to \mu^+\nu_\mu\mathbf{e}^+\nu_\mathbf{e}\mathbf{jj}$

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: $\overline{\mathrm{MS}}$ as for NNPDF.
- Scales: factorisation and renormalisation scale, [MP: $\mu_R = \mu_F = \mu$.

$$\mu = \sqrt{p_{\mathrm{T,j_1}}\, p_{\mathrm{T,j_2}}}, \tag{1}$$

where the jets are the tagging jets.]

- α: G_μ scheme with:

$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_{\mathrm{W}}^2 \left(1 - \frac{M_{\mathrm{W}}^2}{M_{\mathrm{Z}}^2}\right) \qquad \text{with} \qquad G_\mu = 1.16637 \times 10^{-5}\,\mathrm{GeV}. \tag{2}$$

The numerical value is: $\alpha = 7.555310522369 \times 10^{-3}$.
- Mass and width of the massive particles:

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

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

$$M_V = M_V^{\mathrm{OS}} / \sqrt{1 + (\Gamma_V^{\mathrm{OS}}/M_V^{\mathrm{OS}})^2}\,, \qquad \Gamma_V = \Gamma_V^{\mathrm{OS}} / \sqrt{1 + (\Gamma_V^{\mathrm{OS}}/M_V^{\mathrm{OS}})^2}. \tag{4}$$

Hence the numerical values are

$$\begin{aligned} M_{\mathrm{Z}} &= 91.1534806191827\,\mathrm{GeV}, & \Gamma_{\mathrm{Z}} &= 2.494266378772824\,\mathrm{GeV}, \\ M_{\mathrm{W}} &= 80.3579736098775\,\mathrm{GeV}, & \Gamma_{\mathrm{W}} &= 2.084298998278219\,\mathrm{GeV}. \end{aligned} \tag{5}$$

- 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:

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

Contact person	Code	$\mathcal{O}(\alpha^6)$ $\lvert s\rvert^2/$ $\lvert t\rvert^2/\lvert u\rvert^2$	$\mathcal{O}(\alpha^6)$ 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	No virt.	No	No

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

with

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

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:

$$p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}, \qquad |y_\ell| < 2.5, \qquad \Delta R_{\ell\ell} > 0.3. \tag{8}$$

- Missing energy cut:

$$E_{\mathrm{T,miss}} = p_{\mathrm{T,miss}} > 40\,\mathrm{GeV} \tag{9}$$

- Jet definition:

$$p_{\mathrm{T,j}} > 30\,\mathrm{GeV}, \qquad |y_{\mathrm{j}}| < 4.5, \qquad \Delta R_{\mathrm{j}\ell} > 0.3. \tag{10}$$

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

$$m_{\mathrm{jj}} > 500\,\mathrm{GeV}, \qquad |\Delta y_{\mathrm{jj}}| > 2.5. \tag{11}$$

[MP: Now the $\Delta R_{\mathrm{j}\ell}$ 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 BONSAY: 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).
- [MP: $p_{\mathrm{T,j_1,j_2,j_3}}$ and $y_{\mathrm{j_1,j_2,j_3}}$ of the two tagged jets and also the third jet at NLO] (not their sum)
$p_{\mathrm{T,j_1,j_2}}$: [0; 1 TeV] with bins of size 25 GeV (40 bins).
[MP: $p_{\mathrm{T,j_3}}$: [0; 1 TeV] with bins of size 10 GeV (100 bins).]
[MP: $y_{\mathrm{j_1,j_2,j_3}}$: $[-5; 5]$ 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 μ^+, e^+ [MR: and j_3] :
$z_x^* = |y_x - \left(y_{\mathrm{j_1}} + y_{\mathrm{j_2}}\right)/2|/|\Delta y_{\mathrm{jj}}|$
[0; 1.5] with bins of size 0.05 (30 bins).
- $|\Delta y_{\mathrm{jj}}|$: [MR: [0; 10]] with bins of size 0.5 (20 bins).

0.4 Numerical results

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

0.4.2 NLO $\mathcal{O}(\alpha^6\alpha_\mathrm{s})$

0.5 Plan

The plan is:
- Scan in m_{jj} and $|\Delta y_{\mathrm{jj}}|$ at LO and compute the EW, QCD and interference (for the one who can) contribution.
The binning in m_{jj} is $[0, 50, 100, ..., 450, 500, 550, 600, 650, 700, 750, 800]$. These are 17 bins.
The binning in $|\Delta y_{\mathrm{jj}}|$ is $[0, 0.5, 1.0, 1.5, ..., 4.5, 5.0]$. These are 11 bins.

Code	σ[fb]
POWHEG	1.5573 ± 0.0003
Recola +MoCaNLO	1.5503 ± 0.0003
VBFNLO	1.5540 ± 0.0002
BONSAY	1.5524 ± 0.0002
WHIZARD	1.5539 ± 0.0004
MG5_aMC	1.547 ± 0.001

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

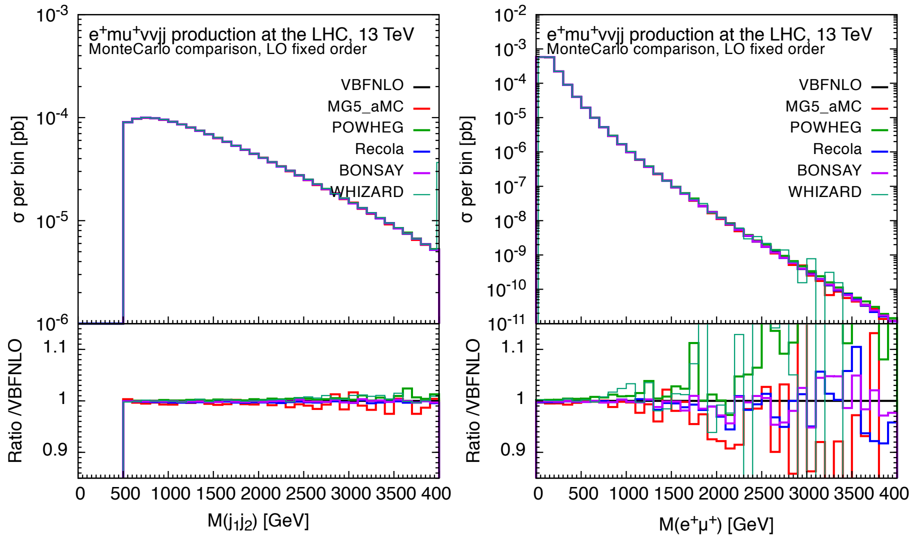

Figure 1: Invariant-mass of the two tagging jets (left) and of the two leptons (right), at LO.

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

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

- 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).

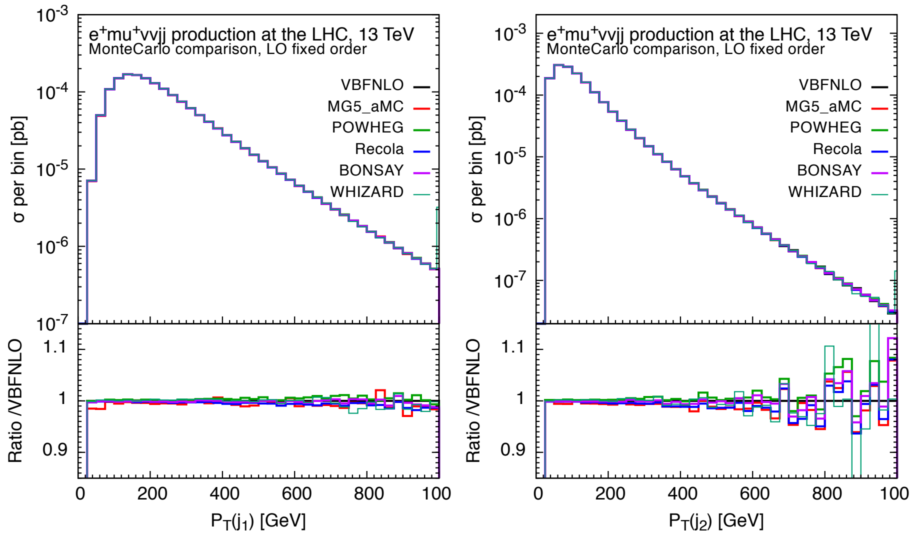

Figure 2: Transverse momentum of the first (left) and second (right) tagging jet, at LO.

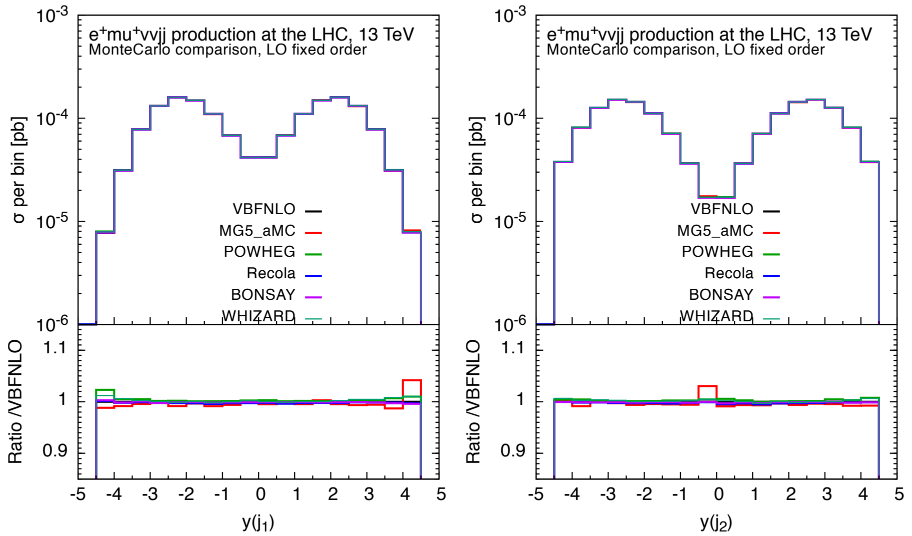

Figure 3: Rapidity of the first (left) and second (right) tagging jet, at LO.

0.6 Remarks

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

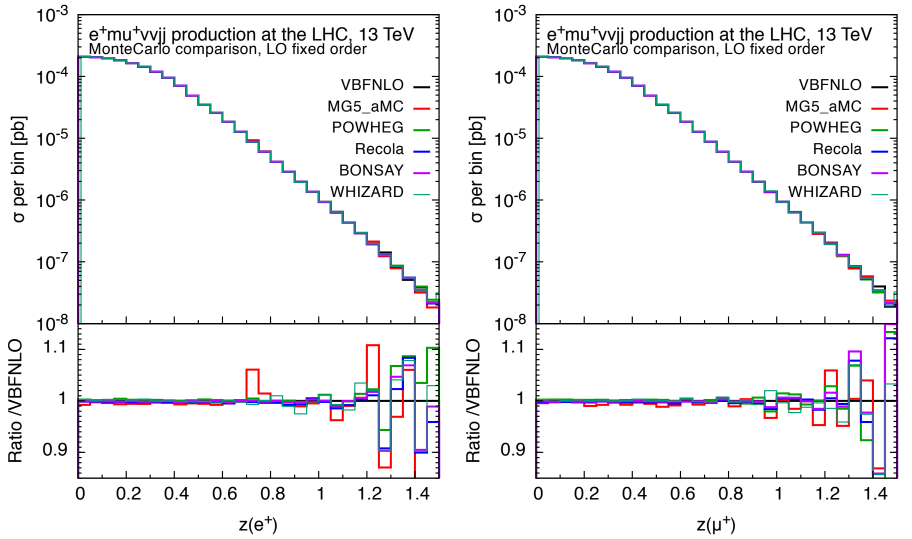

Figure 4: Zeppenfeld variable of the positron (left) and of the muon (right), at LO.

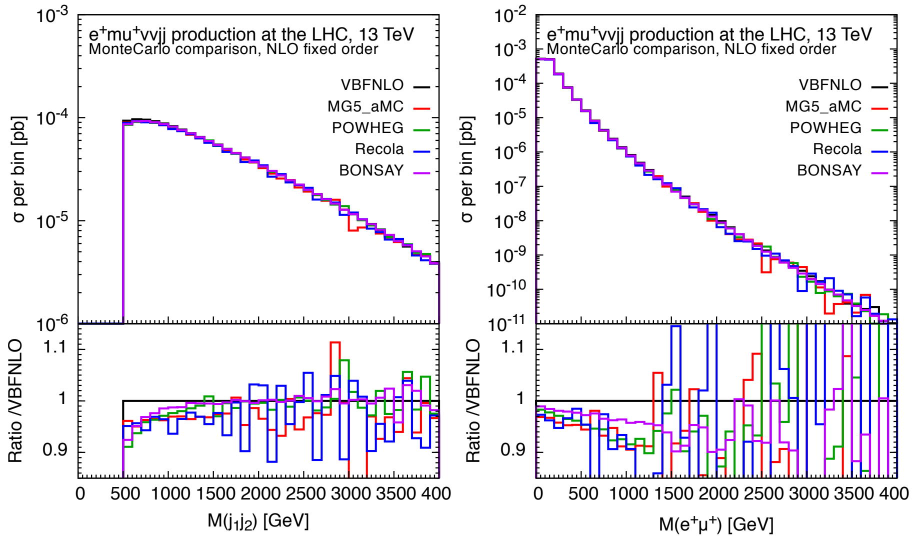

Figure 5: Invariant-mass of the two tagging jets (left) and of the two leptons (right), at NLO.

0.7 Matching to parton shower

Same setup and observables as for the fixed-order runs.

Tools:

- VBFNLO + Herwig7: dipole vs angular-ordered shower, check also MC@NLO vs Powheg matching

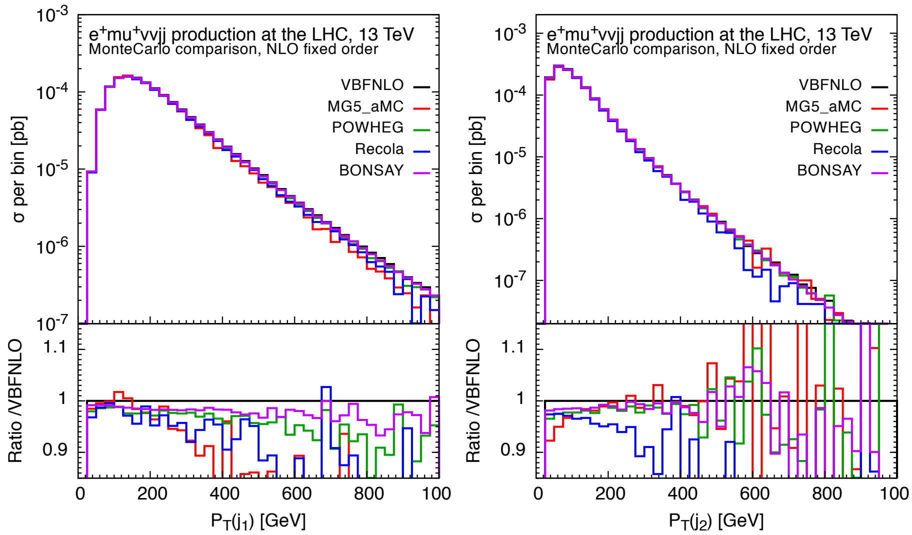

Figure 6: Transverse momentum of the first (left) and second (right) tagging jet, at NLO.

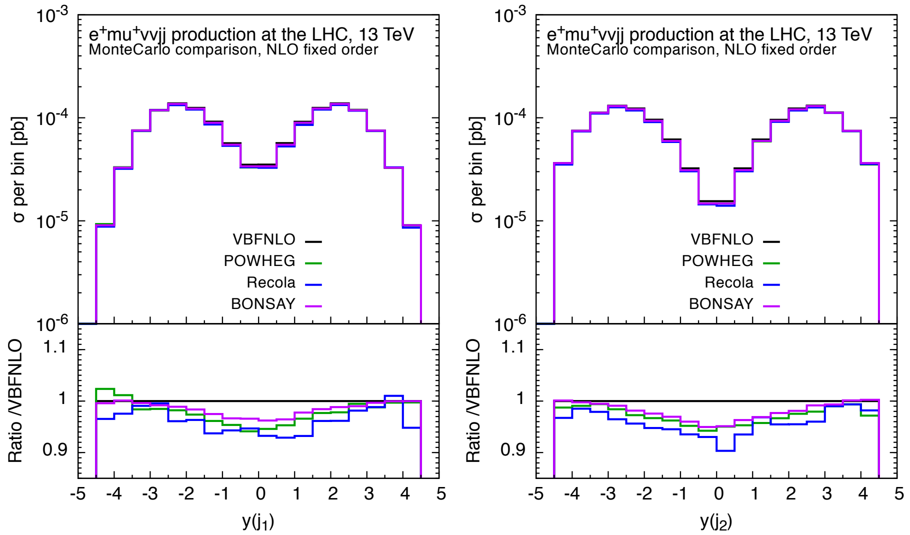

Figure 7: Rapidity of the first (left) and second (right) tagging jet, at NLO.

- MG5_aMC: Pythia8 vs Herwig++
- Powheg + Pythia8
- Whizard + Pythia6 / Pythia8 (MLM merging)
- Phantom + Pythia

Comparisons are done after shower and hadronization. Hadrons are kept stable (no $\pi \to 2\gamma$ decay, no B decay) in order not to have extra photons/leptons

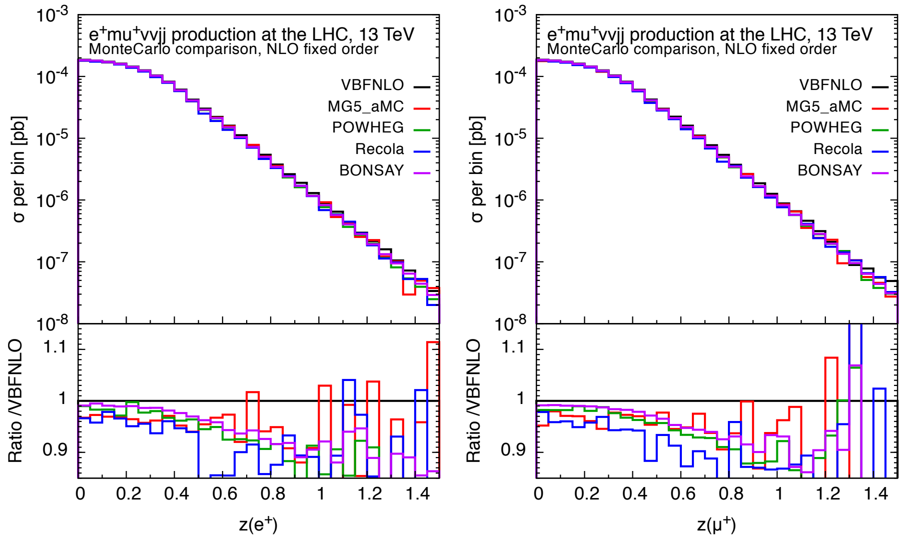

Figure 8: Zeppenfeld variable of the positron (left) and of the muon (right), at NLO.

in the final state.
No underlying event is simulated.
QED radiation is disabled in the shower.
For Pythia8, the Monash tune (number 14) should be used.
All other parameters, in particular those for which particular settings need to be employed e.g. for consistency with the matching method, are free to be changed.

For Pythia8 this amounts to setting

```
pythia.readString("PartonLevel:All = on");
pythia.readString("HadronLevel:All = on");
pythia.readString("HadronLevel:Decay = off");
pythia.readString("PartonLevel:MPI = off");
pythia.readString("BeamRemnants:primordialKT = off");
pythia.readString("SpaceShower:QEDshowerByQ = off");
pythia.readString("SpaceShower:QEDshowerByL = off");
pythia.readString("TimeShower:QEDshowerByQ = off");
pythia.readString("TimeShower:QEDshowerByL = off");
pythia.readString("TimeShower:QEDshowerByOther = off");
pythia.readString("TimeShower:QEDshowerByGamma = off");
pythia.readString("Tune:pp = 14");
```

Part III

Conclusion

Part IV

Acknowledgments

Karlsruhe for hosting the documents used for the comparison.