# Monte-Carlo Uncertainties for Higgs Boson Production in Vector Boson Fusion

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Work done in collaboration with Barbara Jäger, Simon Plätzer, Johannes Scheller and Marco Zaro (Eur.Phys.J.C 80 (2020) 8, 756)

# Introduction

- Discussions about parton shower uncertainties receiving a lot of interest currently within the LHCHXSWG and in the wider community
- For VBF this discussion has been ongoing for some years
- Some third jet observables have been known to be very sensitive to parton showers from studies in similar process (eg VBS) and word-of-mouth studies
- This study meant to make quantitative statements about parton showers and VBF to address these concerns
- Make some recommendations to the experimental community about how various generators are to be used in order to provide reliable predictions

# From 1909.02845 (ATLAS)

| Uncertainty source | $\frac{\Delta\sigma_{\text{ggF}}}{\sigma_{\text{ggF}}}$ [%] | $\frac{\Delta\sigma_{\text{VBF}}}{\sigma_{\text{VBF}}}$ [%] | $\frac{\Delta\sigma_{WH}}{\sigma_{WH}}$ [%] | $\frac{\Delta\sigma_{ZH}}{\sigma_{ZH}}$ [%] | $\frac{\Delta\sigma_{t\bar{t}H+tH}}{\sigma_{t\bar{t}H+tH}}$ [%] |
|---|---|---|---|---|---|
| Statistical uncertainties | 6.4 | 15 | 21 | 23 | 14 |
| Systematic uncertainties | 6.2 | 12 | 22 | 17 | 15 |
| Theory uncertainties | 3.4 | 9.2 | 14 | 14 | 12 |
| Signal | 2.0 | 8.7 | 5.8 | 6.7 | 6.3 |
| Background | 2.7 | 3.0 | 13 | 12 | 10 |
| Experimental uncertainties (excl. MC stat.) | 5.0 | 6.5 | 9.9 | 9.6 | 9.2 |
| Luminosity | 2.1 | 1.8 | 1.8 | 1.8 | 3.1 |
| Background modeling | 2.5 | 2.2 | 4.7 | 2.9 | 5.7 |
| Jets, $E_{\text{T}}^{\text{miss}}$ | 0.9 | 5.4 | 3.0 | 3.3 | 4.0 |
| Flavor tagging | 0.9 | 1.3 | 7.9 | 8.0 | 1.8 |
| Electrons, photons | 2.5 | 1.7 | 1.8 | 1.5 | 3.8 |
| Muons | 0.4 | 0.3 | 0.1 | 0.2 | 0.5 |
| $\tau$-lepton | 0.2 | 1.3 | 0.3 | 0.1 | 2.4 |
| Other | 2.5 | 1.2 | 0.3 | 1.1 | 0.8 |
| MC statistical uncertainties | 1.6 | 4.8 | 8.8 | 7.9 | 4.4 |
| Total uncertainties | 8.9 | 19 | 30 | 29 | 21 |

Recent Higgs combination study shows that theory uncertainties are dominating in the VBF channel despite "good" theoretical understanding of the process. See also Zhijun Liang's talk yesterday

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# Outline

- Validity of VBF approximation (HJets vs VBFNLO) + H7
- Impact of shower starting scale in MG5_aMC and comparison between PY8 and H7
- Impact of `hdamp` in POWHEG and comparison between PY8 and H7
- Impact of scale variations inside Matchbox + H7
- Jet radius dependence
- "Best" predictions for all generators
- Note: Only studying parton shower, no MPI, hadronisation etc. Leave this for future studies

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# Setup

- Tuned comparison between NLO+PS generators POWHEG+(PY8/H7), MG5_aMC+(PY8/H7) and Matchbox+Herwig framework, and fixed order proVBFH (NNLO)
- Testing a range of matching procedures, recoil schemes and internal parameters (shower starting scale, `hdamp` etc)
- Use common setup with PDF4LHC15_nnlo_100_pdfas, $\sqrt{s} = 13$ TeV

VBF cuts:

$$|y_j| < 4.5, \qquad p_{t,j} > 25 \text{ GeV}$$

$$m_{jj} > 600 \text{ GeV}, \quad |\Delta y_{j_1 j_2}| > 4.5, \quad y_{j_1} y_{j_2} < 0$$

Jets defined as anti-$k_t$ with $R = 0.4$ by default

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# Setup

| generator | matching | SMC | shower recoil | used in Sec. 4.2 |
|---|---|---|---|---|
| VBFNLO+Herwig7/Matchbox | $\oplus$ | HERWIG 7.1.5 | global ($\tilde{q}$) / local (dipole) | ✓ ($\tilde{q}$) |
| HJets+Herwig7/Matchbox | $\oplus$ | HERWIG 7.1.5 | global ($\tilde{q}$) / local (dipole) | |
| MadGraph5_aMC@NLO 2.6.1 | $\oplus$ | HERWIG 7.1.2 | global | ✓ |
| MadGraph5_aMC@NLO 2.6.1 | $\oplus$ | PYTHIA 8.230 | global | |
| POWHEG BOX V2 | $\otimes$ | PYTHIA 8.240 | local (dipole) | ✓ |
| POWHEG BOX V2 | $\otimes$ | PYTHIA 8.240 | global | |
| POWHEG BOX V2 | $\otimes$ | HERWIG 7.1.4 | global ($\tilde{q}$) | |

Many different variations possible

- Generator
- Matching scheme
- Shower (angular/dipole)
- Recoil (global/local)

Plus intrinsic generator variations, $\mu_R$, $\mu_F$ etc.

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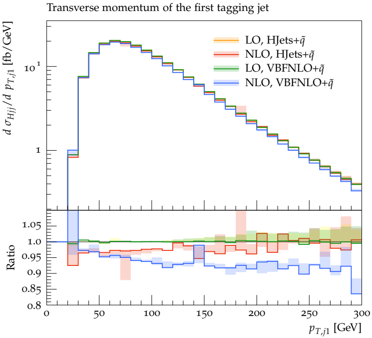
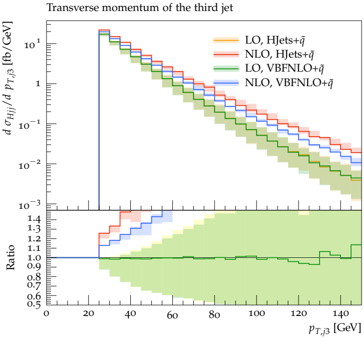
# Quality of VBF approximation




- Comparison between the full calculation (HJets) and approximation (VBFNLO) shows very good agreement within our tight VBF cuts
- Outside these cuts significant differences arise (relevant for STXS and more inclusive measurements) at NLO

$$|\eta_{jj}| > 1, \quad m_{jj} > 200\text{ GeV}$$

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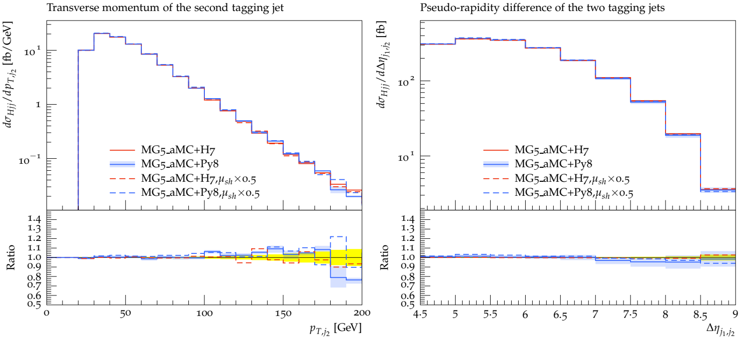
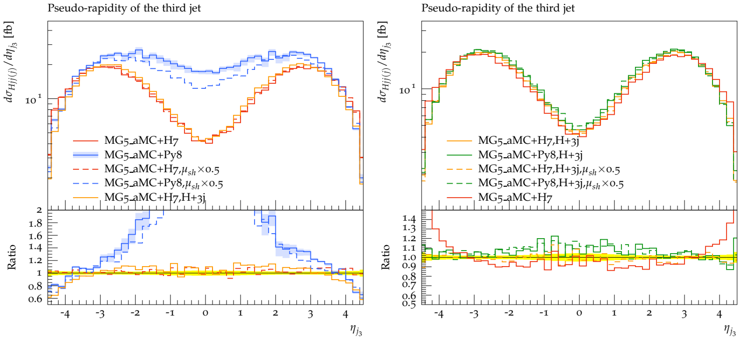
# Intrinsic uncertainties in MG5



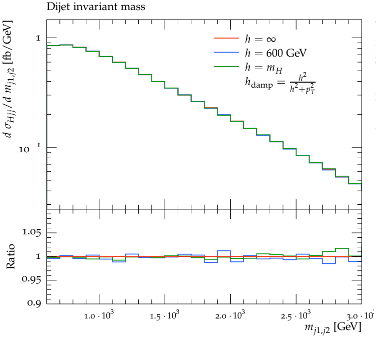

- MG5_aMC shown here matched to H7 and PY8
- To asses intrinsic theory uncertainties in MG5_aMC we may vary the shower starting scale, $Q_{sh}$
- For hard observables very good agreement between the two showers - within scale variations

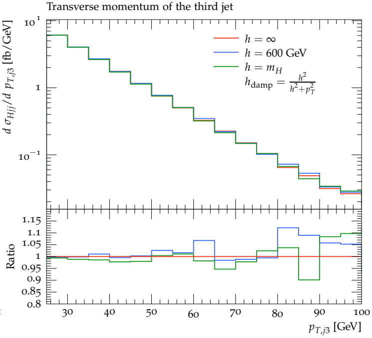
# Intrinsic uncertainties in MG5




- When considering third jet observables very large discrepancies outside of the scale variation can be observed
- If one includes NLO corrections this discrepancy disappears and very good agreement is found with the lower order prediction matched to H7
- PY8 mathcing clearly leads to unphysical predictions

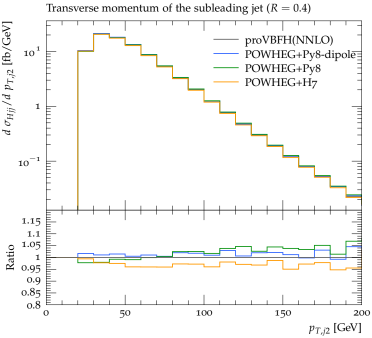
# Intrinsic uncertainties in POWHEG

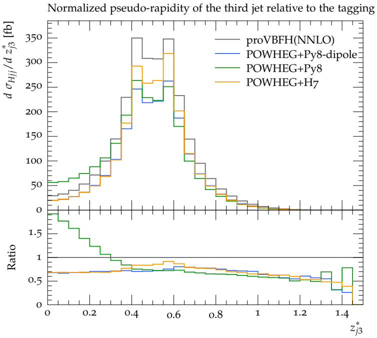



- In POWHEG we may vary `hdamp` in order to asses the "matching" uncertainties
- We find that this variation has almost no impact on the results
- Here results shown interfaced to PY8 with dipole recoil

# Intrinsic uncertainties in POWHEG




- POWHEG can be matched to H7 and PY8. Here we pick angular ordered H7 and PY8 with both its default recoil and a local initial-final recoil
- Only small differences for hard observables
- For the third jet we see the same “unphysical” behaviour of PY8 with its default recoil scheme, although the effect is smaller than in MG5_aMC due to POWHEG handling the first emission itself

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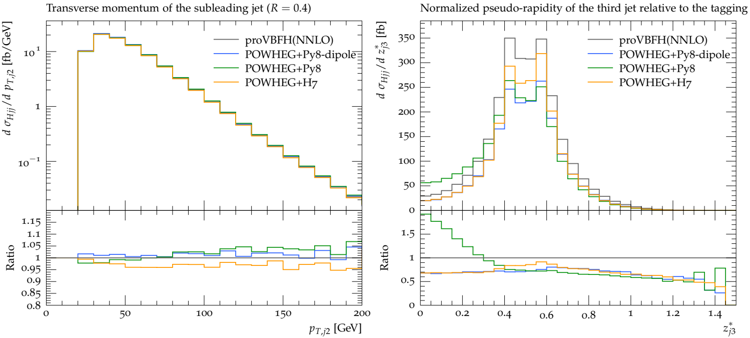
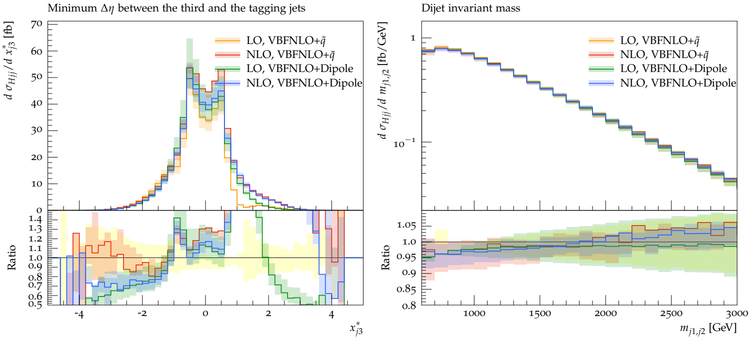
# Intrinsic uncertainties in POWHEG




- POWHEG can be matched to H7 and PY8. Here we pick angular ordered H7 and PY8 with both its default recoil and a local initial-final recoil
- Only small differences for hard observables

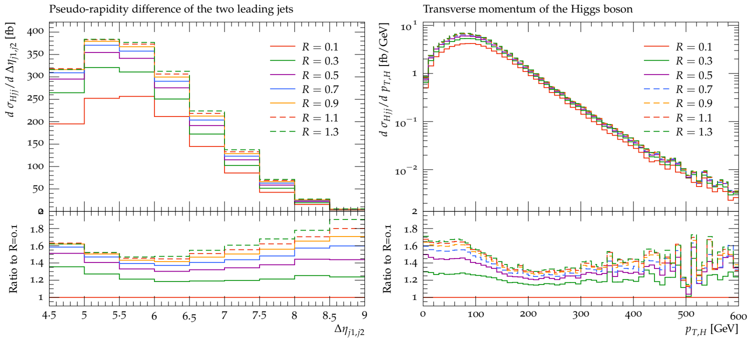
$$z^*_{j3} = \frac{\eta_{j3} - \frac{\eta_{j_2} + \eta_{j_1}}{2}}{|\Delta\eta_{j_1,j_2}|}$$

# Intrinsic uncertainties in Matchbox + H7




- In H7 we have access to both an angular ordered and a dipole shower
- Differences between the two contained within scale variation (hard scale of shower evolution plus $\mu_F$ and $\mu_R$) for hard observables
- Larger differences observed in third jet observables

# Jet radii




- Largeness of QCD corrections in VBF related to radiation outside of jet cone
- In general expect to find logarithmic dependence on $R$
- Varying $R$ around $R = 0.4$ we see $\mathcal{O}(10\%)$ differences in shape and normalisation

# Best predictions

| generator | matching | SMC | shower recoil | used in Sec. 4.2 |
|---|---|---|---|---|
| VBFNLO+Herwig7/Matchbox | $\oplus$ | HERWIG 7.1.5 | global ($\tilde{q}$) / local (dipole) | ✓ ($\tilde{q}$) |
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| POWHEG BOX V2 | $\otimes$ | PYTHIA 8.240 | local (dipole) | ✓ |
| POWHEG BOX V2 | $\otimes$ | PYTHIA 8.240 | global | |
| POWHEG BOX V2 | $\otimes$ | HERWIG 7.1.4 | global ($\tilde{q}$) | |

Based on the above we select three setups as our “best” prediction for each generator. We compare against a fixed order NNLO calculation (proVBFH).

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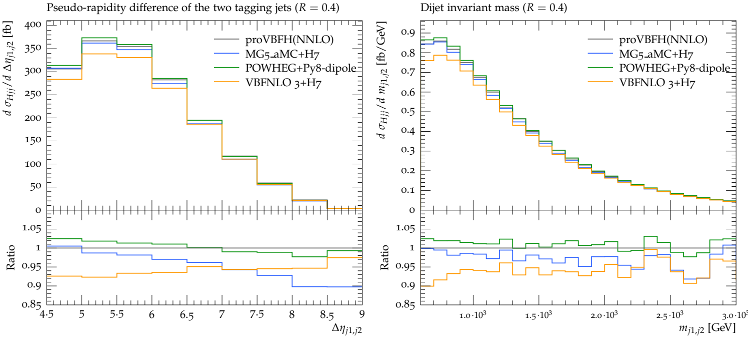
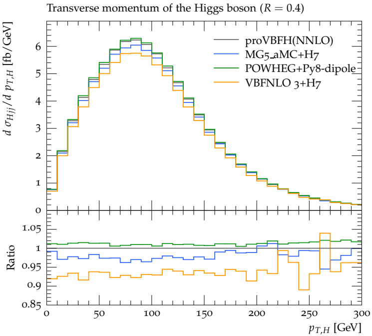
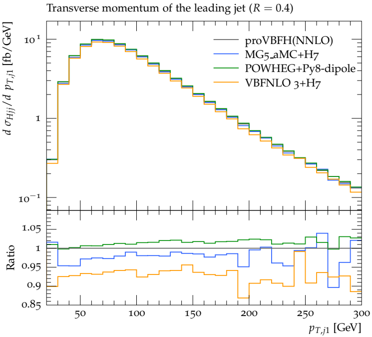
# Comparing all generators




- Comparing all generators we see a clear picture
- For hard observables we find some shape differences, typically at the $\mathcal{O}(10\%)$
- However, this effect shrinks if one were to compare normalised distributions

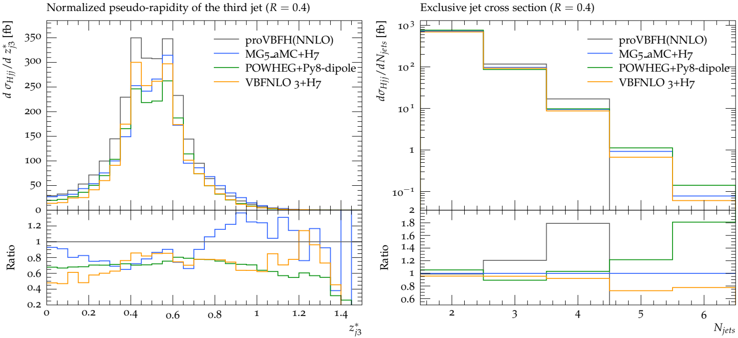
# Comparing all generators




- For very inclusive quantities one sees more or less only differences due to normalisation
- Given that the VBF cross section is very sensitive to the jet definition, it is not unlikely that the agreement could be improved upon by using a slightly larger $R$
- No conclusion from this study, but worth looking into

# Comparing all generators




- When considering higher jet multiplicities the discrepancies increase a lot
- Not surpising given less robust hard perturbative input
- In particular the Monte Carlos predict significantly fewer jets than the fixed order calculation

# Conclusions

- Large effort in studying Parton Shower effects in VBF finally done
- VBF insensitive to NLO matching prescription but very sensitive to recoil scheme inside PY8
- For H7 this does not seem to be the case
- Not one “best” prediction but a number of physically sound predictions
- The uncertainties are typically below 10%, and are dominated by differences in normalisation rather than shapes for most observables
- Studies of jet radius dependence would be valuable (see also Les Houches)
- RIVET analyis made public