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Theoretical comparison for VBS production of W^+W^+

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To appear as 1803.XXXXX in collaboration with
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Vincent Rothe, Christopher Schwan, Pascal Stienemeier & Marco Zaro[1]

[1] Many slides stolen from Giovanni and Marco's talk last month

Outline

- Introduction
  - Definition of process
  - Codes used
- Inclusive Study
  - Where does the VBS approximation break down?
- Fiducial Study
  - How big are the discrepancies in the usual VBS volume?
- Parton Shower Systematics
  - How big are the shower and matching uncertainties?
  - Do we understand these differences?
- Conclusion

Introduction

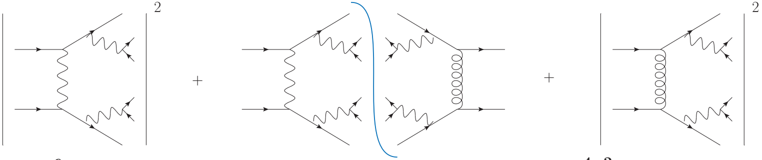
Project aims within WG1

- Compare all[2] available Monte Carlo generators which simulate VBS
  - Quantify the discrepancy between the codes due to various approximations used at LO and NLO
  - Do this both inclusively and under typical VBS cuts (use above to define fiducial volume)
  - Investigate uncertainties due to parton shower and matching prescription
- Outcome of project:
  - Peer-reviewed paper (soon)
  - A set of recommendations for the experimentalists regarding the simulation of VBS processes

[2] almost

Investigated LO and NLO contributions to VBS

LO: α^6, $\alpha^5\alpha_s$ and $\alpha^4\alpha_s^2$

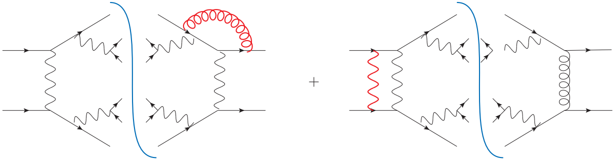


$\alpha^{\mathbf{6}}$: signal

$\alpha^{\mathbf{5}}\alpha_{\mathbf{s}}$: interference

$\alpha^{\mathbf{4}}\alpha_{\mathbf{s}}^{\mathbf{2}}$: QCD background

NLO QCD: $\alpha^6\alpha_s$ (not the end of the story, `arXiv:1708.00268`)

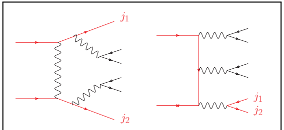


$\alpha^{\mathbf{6}}\alpha_{\mathbf{s}}$: QCD correction of the signal α^6

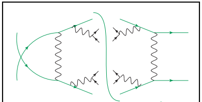
$\alpha^{\mathbf{6}}\alpha_{\mathbf{s}}$: EW correction of the interference $\alpha^5\alpha_s$

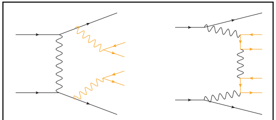
Codes

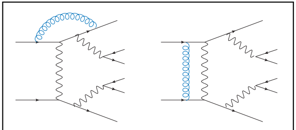
CODE	$\mathcal{O}(\alpha^6)$ s, t, u	$\mathcal{O}(\alpha^6)$ interf.	Non-res.	NLO	NF QCD	EW corr. to $\mathcal{O}(\alpha_s \alpha^5)$
BONSAY	t/u	No	Yes, virt. No	Yes	No	No
POWHEG	t/u	No	Yes	Yes	No	No
MG5_AMC	Yes	Yes	Yes	Yes	No virt.	No
MOCANLO+RECOLA	Yes	Yes	Yes	Yes	Yes	Yes
PHANTOM	Yes	Yes	Yes	No	-	-
VBFNLO	Yes	No	Yes	Yes	No	No
WHIZARD	Yes	Yes	Yes	No	-	-

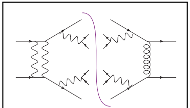


$\mathbf{t}$ − channel $\mathbf{s}$ − channel


t/u interference at $\mathcal{O}(\alpha^6)$


resonant non-resonant

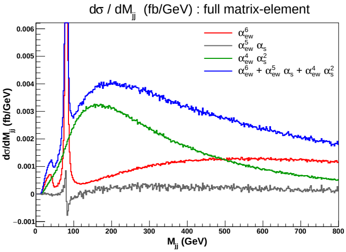

factorizable QCD corr. non-factorizable QCD corr.

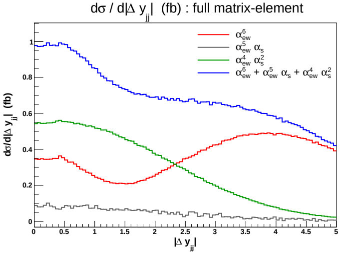

EW corr. to $\alpha^5 \alpha_s$

Inclusive study

Inclusive LO study: three perturbative orders

Inclusive: events with any M_{jj} and Δy_{jj}. (PHANTOM results shown)





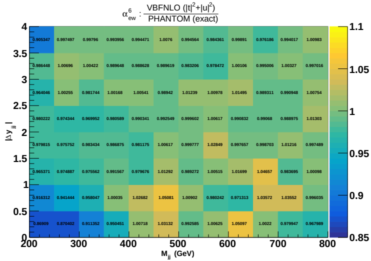
VBF cuts $M_{jj} > 500$ GeV, $|\Delta y_{jj}| > 2.5$ enable isolation of the EW signal from the QCD background; interference is small.

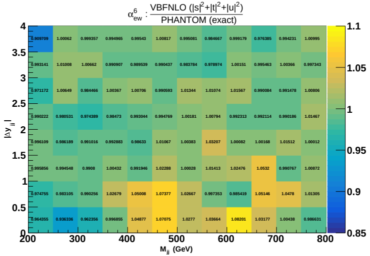
Region	$\sigma[\text{fb}](\mathcal{O}(\alpha^6))$	$\sigma[\text{fb}](\mathcal{O}(\alpha_s^2\alpha^4))$	$\sigma[\text{fb}](\mathcal{O}(\alpha_s\alpha^5))$	$\mathcal{O}(\alpha^6)$/tot
inclusive	2.29(2)	1.47(7)	0.22(3)	57 %
fiducial	1.43(7)	0.17(4)	0.048(8)	86 %

Full ME codes agree pretty well: discrepancies $\lesssim 1$ %.

Inclusive LO study: VBS approx. at LO EW

VBS approximation: neglects s–channels, t/u interferences (and non-factorizable QCD corr. at NLO). (VBFNLO, PHANTOM results shown)





VBS approx. $\rightarrow$ VBS approx. + s–channels

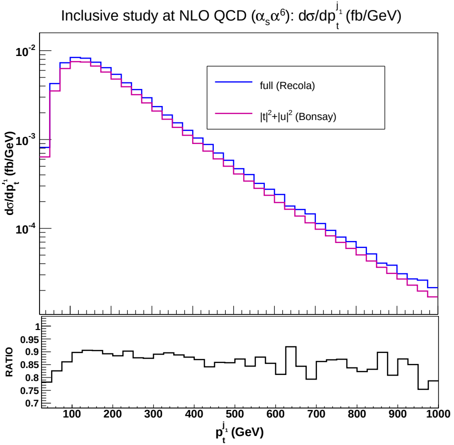
In the M_W peak region the s–channels cannot be neglected: VBS approx. fails for $M_{jj} < 200$ GeV, $|\Delta y_{jj}| < 2$, otherwise good agreement with full calc. (at most 4 % discrep.).

Inclusive NLO QCD study

A little less inclusive than LO: $M_{jj} > 200$ GeV, $|\Delta y_{jj}| > 2$.

(Recola, Bonsay results shown)

Full ME vs approx. ($|t|^2 + |u|^2$)



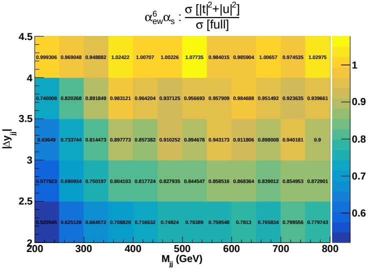
Larger discrepancies (up to $\approx 20\%$) than in the fiducial region.

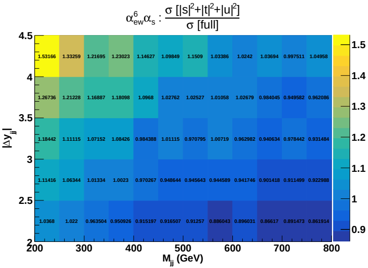
s–channels are less suppressed, due to $M_{jj} > 200$ GeV (rather than 500 GeV) and the NLO QCD corrections (extra jet).

Preliminary results

Inclusive NLO QCD study: adding s–channels

VBS approx. at NLO: s–channels are required to cure the discrepancies w.r.t. full ME in the low M_{jj} - low Δy_{jj} region.





VBS approx. $\rightarrow$ VBS approx. + s–channels

But still large discrepancies for $[M_{jj} \lesssim 400$ GeV, $|\Delta y_{jj}| \gtrsim 3]$ ($\approx 20\%$) and $[M_{jj} \gtrsim 500$ GeV, $|\Delta y_{jj}| \lesssim 2.5]$ ($\approx 15\%$)

Fiducial study

Set-up

$pp \to jje^+\nu_e\mu^+\nu_\mu$, $\sqrt{s} = 13$ TeV

PDFs: NNPDF30 at NLO, with $\alpha_s(M_Z) = 0.118$ arXiv:1410.8849
Scales: dynamical, $\mu_R = \mu_F = \sqrt{p_{t,j_1} p_{t,j_2}}$
Complex Mass Scheme arXiv:hep-ph/9904472

Cuts inspired by arXiv:1405.6241, arXiv:1410.6315

- 2 (3, NLO) anti–k_t jets (arXiv:0802.1189) with $R = 0.4$, $|y_j| < 4.5$, $p_t^j > 30$ GeV, $|\Delta R_{j\ell}| > 0.3$
- 2 hardest jets: $M_{jj} > 500$ GeV, $|\Delta y_{jj}| > 2.5$
- 2 charged leptons: $|y_\ell| < 2.5$, $p_t^\ell > 20$ GeV, $|\Delta R_{\ell\ell}| > 0.3$
- $p_t^{miss} > 40$ GeV

Codes

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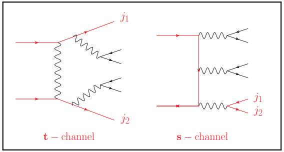
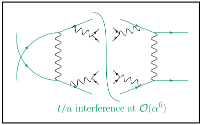
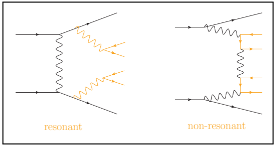
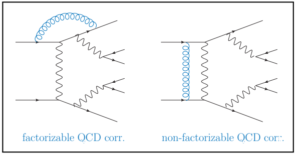
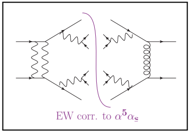
POWHEG	t/u	No	Yes	Yes	No	No
MG5_AMC	Yes	Yes	Yes	Yes	No virt.	No
MOCANLO+RECOLA	Yes	Yes	Yes	Yes	Yes	Yes
PHANTOM	Yes	Yes	Yes	No	-	-
VBFNLO	Yes	No	Yes	Yes	No	No
WHIZARD	Yes	Yes	Yes	No	-	-





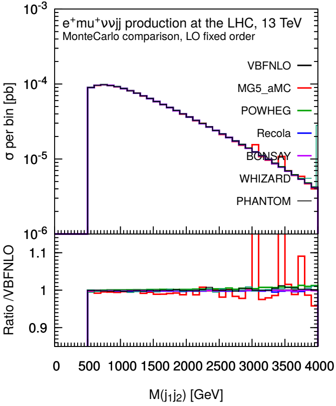






Comparison at $\mathcal{O}(\alpha^6)$

LO VBS signal: agreement at the $\mathcal{O}(1\%)$ level



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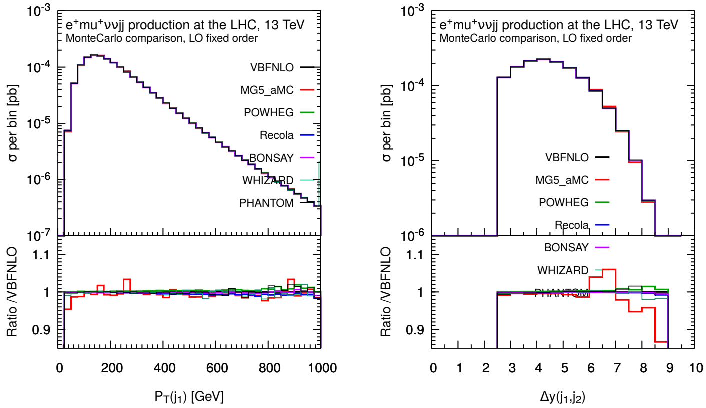
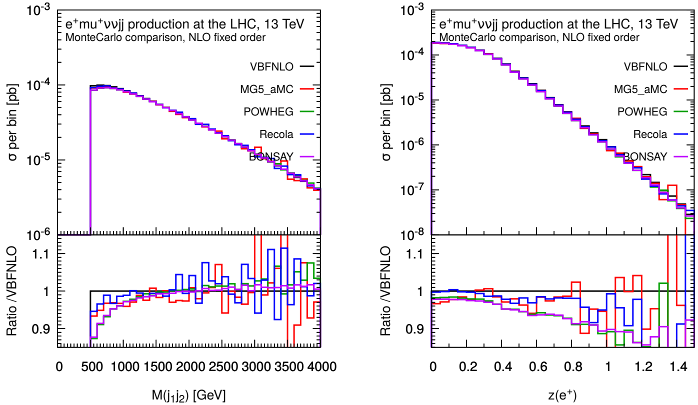


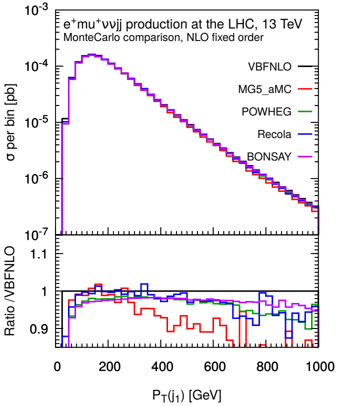
Comparison at $\mathcal{O}(\alpha^6\alpha_s)$

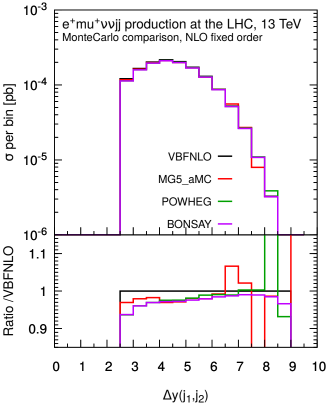
NLO VBS signal: discrepancies due to the various approximations at the $\mathcal{O}(10\%)$ level



Comparison at $\mathcal{O}(\alpha^6\alpha_s)$

NLO VBS signal: discrepancies due to the various approximations at the $\mathcal{O}(10\%)$ level





Parton Shower Systematics

Tool comparison at NLO+PS

- The plan is to compare predictions from
  - Powheg+PY8
  - MG5_aMC@NLO+(PY8, HW++)
  - VBFNLO+Herwig7
  - Phantom+PY8 (LO only)
- Predictions are done after hadronization (no MPI)
- Try as much as possible to use common shower-parameters (not always possible with different showers / matching schemes)
- Same setup/analysis cuts as for the fixed-order comparison

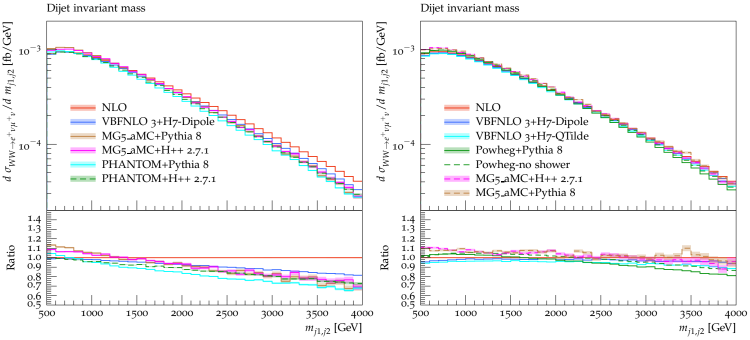
Rates within cuts

	Code	σ[fb]
NLO	MG5_aMC+Pythia8	1.450(1.368)
	MG5_aMC+Herwig++	1.445(1.363)
	POWHEG	1.3633
	VBFNLO	1.339
LO	MG5_aMC+Pythia8 (LO)	1.352(1.275)
	MG5_aMC+Herwig++ (LO)	1.343(1.267)
	PHANTOM+Pythia8	1.235

Note: MG5_aMC has been run with stable W^+, which are decayed by MadSpin. The details of the treatment of Γ_W induce a +6% effect on the cross-section. This effect is compensated in numbers in parentheses.
Note2: we are understanding how to assign the statistical uncertainties

- At the total-cross section level, tools compare rather well, with differences at the 1% level

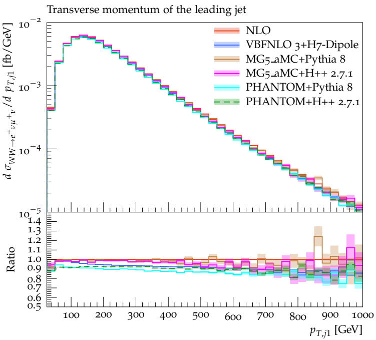
Dijet-invariant mass

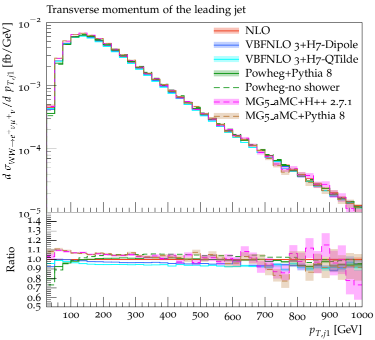


Note: MG5_aMC results have not been rescaled for the 6% width effect

- The inclusion of NLO corrections stabilises the predictions
- NLO+PS results line in a $\sim 10\%$-wide band

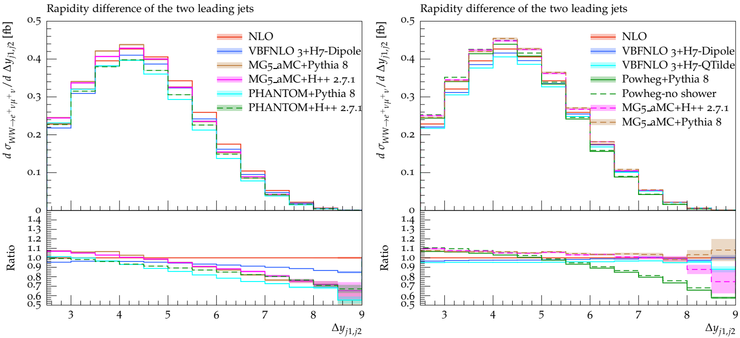
Hardest jet p_T





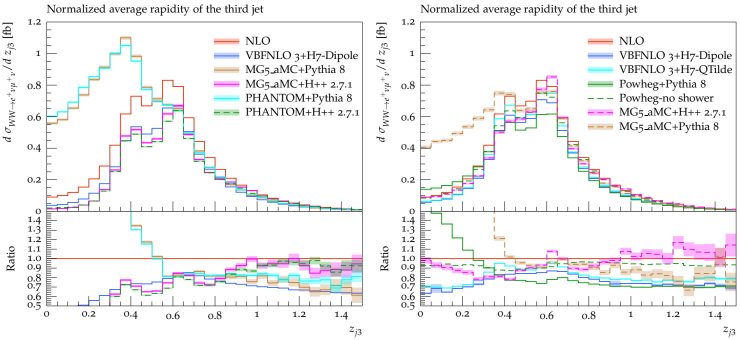
- Slightly larger differences appear in the shape of predictions at NLO+PS, in the low-p_T region

Dijet rapidity separation



- The Powheg prediction shows a different shape at NLO
- This effect is already present before showering (at the LHEF level), and is likely due to the Powheg Sudakov of the first emission

Third jet z variable



- Much larger discrepancies appear for the third jet. In particular Pythia8 tends to enhance the rate in the central region (still to be understood)

$$z_{j_3} = \frac{|y_{j_3} - (y_{j_1} + y_{j_2})/2|}{|\Delta y_{jj}|}$$

Some conclusions...

- First in-depth comparison of MC generators for VBS
- Very good agreement found at LO ($\mathcal{O}(1\%)$) whereas differences grow to $\mathcal{O}(10\%)$ at NLO. These discrepancies understood in terms of the employed approximations
  - Special care has to be taken in inclusive setups, where the VBS approximation breaks down. Here the full result should always be used, both at LO and NLO
- Parton shower uncertainties are also at the $\mathcal{O}(10\%)$-level for most variables.
- For the description of the third jet large discrepancies exists between the generators. This still has to be understood in detail
- To appear on arXiv very soon with final results and recommendations