Vector Boson Scattering in the POWHEG BOX[1]

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VBS Polarization Workshop
Laboratoires Leprince Ringuet

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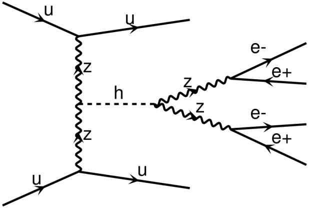
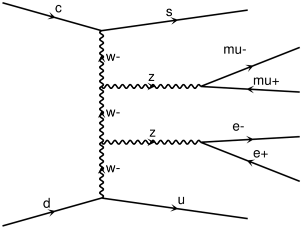
[1] And elsewhere...

Outline

- POWHEG generates unpolarised events $\rightarrow$ no easy way to change that - not impossible though
- With a suitbale set of projectors, POWHEG events can trivially be used to make predictions $\leftarrow$ very hard in the presence of cuts [see A. Ballestrero's talk]
- Nonetheless VBS cuts have come to stay
- Need good understanding of event generators in the presence of cuts
- Recent studies have shown "larger than expected" sensitivity to mathcing and parton shower details for more exclusive variables $\leftarrow$ [this talk]

Vector Boson Scattering

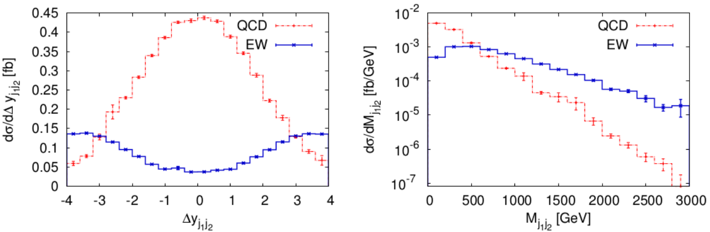




Topology

- Forward tagging jets
- Little central jet activity
- Leptonic decay products (typically) between jets

VBS cuts (ssWW)

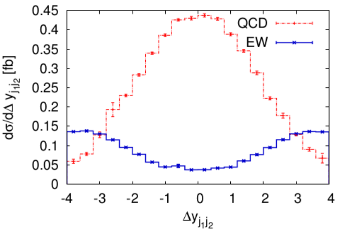


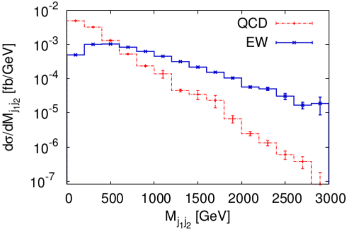
[Jäger, Zanderighi (2011)]

- Central leptons
  - $\eta_{j,min} < \eta_l < \eta_{j,max}$
- High invariant jet mass
  - $M_{jj} > 600\ GeV$

- Separated jets
  - $\eta_{j_1} \cdot \eta_{j_2} < 0$
  - $|\eta_{j_1} - \eta_{j_2}| > 4.0$

VBS cuts (ssWW)





[Jäger, Zanderighi (2011)]

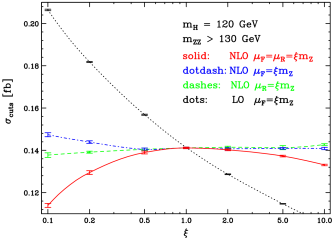
Inclusive NLO results ($p_T^{jet} > 20$ GeV)

$\sigma_{QCD}^{inc} \sim 2.1$ fb $\qquad \sigma_{EW}^{inc} \sim 1.1$ fb

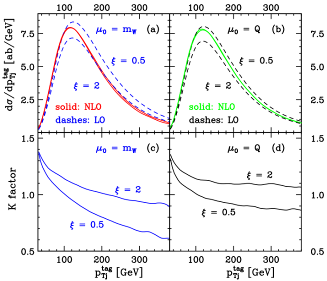
VBF NLO results

$\sigma_{QCD}^{VBF} \sim 0.007$ fb $\qquad \sigma_{EW}^{VBF} \sim 0.2$ fb

Why study NLO-QCD?



[arXiv:hep-ph/0604200, B.Jäger et al.]



[B.Jäger et al. (2010)]

- Precision
- Stability
  - Normalisation of LO results arbitrary
  - Scale dependence reduced to $\sim 2\%$
    - NNLO-QCD VBF H results suggests larger corrections
    - NLO-EW corrections recently shown to be dominant

VBS@NLO-QCD

Fixed order NLO-QCD result for

- $pp \to ZZjj, \quad W^{\pm}W^{\mp}jj, \quad W^{\pm}W^{\pm}jj, \quad W^{\pm}Zjj$

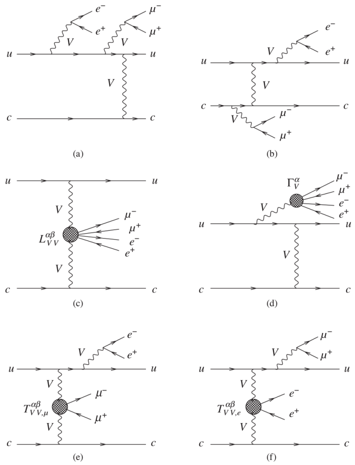
available through `VBFNLO`. [Figy, Oleari, Zeppenfeld (2003)]

- Includes
  - off-shell effects
  - spin correlations
  - s-channel contributions (version used for mathcing did not)
- Excludes
  - t/u-channel interference

S-channel and interference effects found to contribute at the permille level under VBF cuts at LO. At NLO this is no longer true [1803.07943]

[G. Bozzi, C. Oleari, D. Zeppenfeld, B. Jäger (2006-2009)]

Elements of the calculation



- Leptonic tensors for different topologies
- Only corrections to quark lines - self-energy, triangle, box and pentagon
- New physics does not change the QCD structure of amplitudes
- Ideal environment for testing EW structure of the Standard Model

[Bozzi, Jäger, Oleari, Zeppenfeld (2006)]

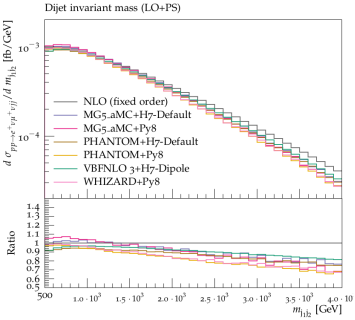
VBS@NLOPS

Many EW $VVjj$ processes and some QCD $VVjj$ processes implemented in the POWHEG-BOX [Alioli, Nason, Oleari, Re (2010)]

- In general high performance clusters are needed to achieve good results
- Uses features of Version 2 of the POWHEG-BOX code
  - the possibility to produce grids in parallel and combine them;
  - the option to modify scales and parton distribution functions a posteriori, through a reweighting procedure of Les Houches events;
  - a faster calculation of upper bounds, and the possibility to store upper bounds and combine them;
  - an improvement in the separation of regions for the real radiation, which results in smoother distributions.
- Here focus on $ssWW$ (1803.07943) but results very similar for all $VVjj$ processes that have been studied

- EW $WWjj$: Jäger, Zanderighi (2011-2013)
- EW $ZZjj$: Jäger, Zanderighi, AK (2013)
- QCD W^+W^+jj: Melia, Nason, Rontsch, Zanderighi (2011)

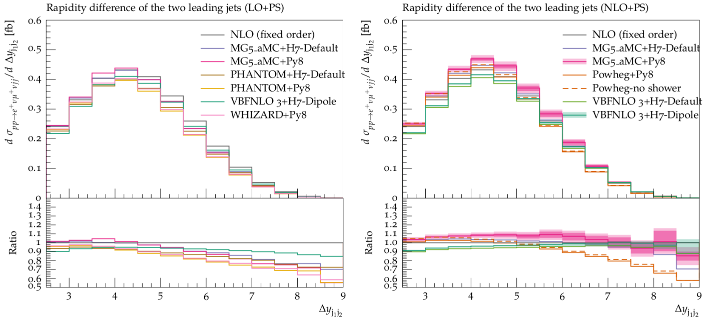
Parton Shower Matching (ssWW)



[1803.07943]

- LO+PS: Large shape distortion with respect to FO NLO. Spread in predictions of ~ 20%
- NLO+PS: Better agreement in shape of NLO, but no appreciable reduction in spread

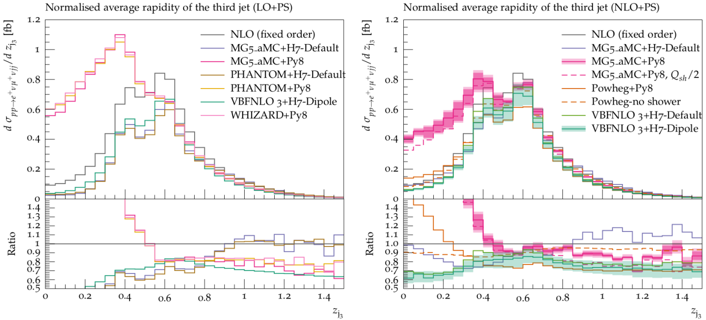
Parton Shower Matching (ssWW)



[1803.07943]

For Δy_{jj} the same conclusion holds, although the discrepancies at NLO+PS perhaps even more striking.

Parton Shower Matching (ssWW)

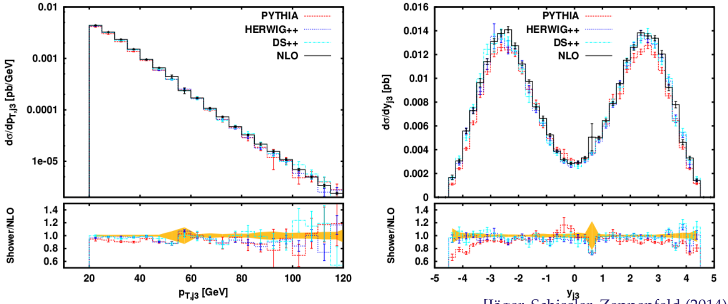


[1803.07943]

For variables related to the third jet, the various predictions are in ~ 100% disagreement.

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

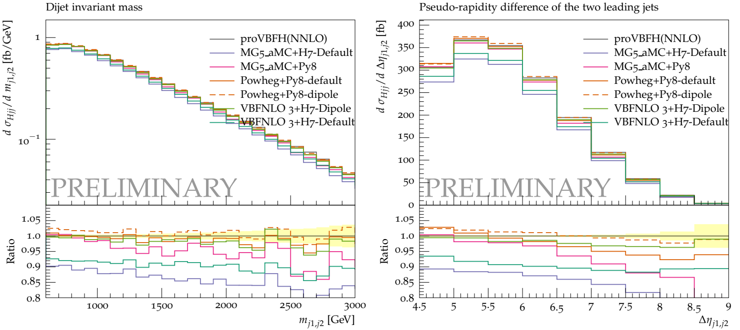
Third jet @ NLO-QCD



[Jäger, Schissler, Zeppenfeld (2014)]

- No *VVjjj* processes at NLO-QCD but VBF *Hjjj*
- Third jet is much more stable under the parton shower
- For VBF NNLO-QCD is also availble
- We can use this to learn something about parton shower mathcing for VBF(S) processes

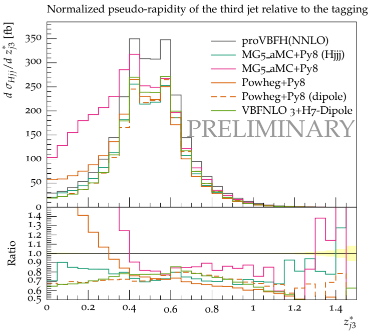
VBF NLOPS

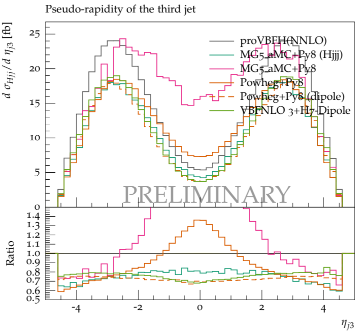


Similar pattern for VBF. Large spread in predictions - significantly outside scale uncertainty band. Observation: Dipole type showers in “best” agreement with fixed order NNLO-QCD.

Work in progress with B. Jäger and M. Zaro

VBF NLOPS





The third jet from NLOPS (Hjj) is in good agreement with NLOPS (Hjjj) when dipole showers are used. Matching details are not very important. Large NLO-QCD corrections likely due to small jet radius (R=0.4).

Work in progress with B. Jäger and M. Zaro

Summary

- Polarisation studies with POWHEG not trivial
  - Either need to modify code to get polarised cross sections,
  - or find suitable operators and expectation values
- NLOPS known for many VBS processes
  - Larger spread in predictions than what scale uncertainty band would suggest
  - VBS variables in particular sensitive to matching procedures and parton shower prescription
  - Third jet very poorly simulated by NLOPS at a first glance
- VBF studied in more detail
  - Discrepancies for third jet seem driven by parton shower
  - Dipole type parton showers in better agreement with higher order calculations
  - Motivated by the t-channel structure of the process (to be investigated)