# VBSCan

Marco Zaro

EWWG meeting @ CERN

14/12/18

Nikhef

NWO
Netherlands Organisation
for Scientific Research

# VBSCan

- https://vbscanaction.web.cern.ch/
- A COST-funded action, started in May 2017
- Connects all main players studying Vector Boson Scattering at hadron colliders (Theory/ATLAS/CMS/Statistics)
- Funds for scientific missions, meetings, dissemination events, etc…
- 24 EU countries + 3 International partner countries (US, BR, CN)
- Everyone can join!

# Working Groups

- **WG1: Theoretical Understanding** - Precision, EFT, polarisation, BSM
  MZ, Mathieu Pellen vbscan-wg1@googlegroups.com
- **WG2: Analysis Techniques** - Analysis building, identification of final states, combination
  Magdalena Slawinska, Roberto Covarelli vbscan-wg2@googlegroups.com
- **WG3: Experimental techniques** - Reconstruction algoritms, new data analysis techniques
  Senka Duric, Lucrezia Bruni vbscan-wg3@googlegroups.com
- **WG4: Knowledge exchange and cross activities**
  Kristin Lohwasser, Ivica Puljak vbscan-wg4@googlegroups.com
- **WG5: Inclusiveness Policies**
  Chara Petridou vbscan-wg5@googlegroups.com

# Meetings and schools:

- Two action-wide in person meetings per grant-period
  - **Kick-off meeting in Split (June 2017)** https://indico.cern.ch/event/629638/ Proceedings: arXiv:1801.04203
  - **Second GP1 meeting at CERN (Feb 2018)** https://indico.cern.ch/event/689505/
  - **2nd annual meeting in Thessaloniki (June 2018)** https://indico.cern.ch/event/706178/ Proceedings: to be published
  - **2nd in-person meeting for GP2 in Ljubljana + Training Event (Feb 2019)** https://indico.cern.ch/event/773206/ https://indico.cern.ch/event/775229/ ← You are welcome to attend!!!
- One school per GP:
  - **EWSB school at Maratea, Italy (Apr 2018)** https://indico.cern.ch/event/673580/
  - **Joint VBSCan+ParticleFace school in 2019** (Desy/Hungary), tba

# Recent workshops

- **VBS Polarisation workshop in Paris (Oct 2018)**
  https://indico.cern.ch/event/744263/
  Discussion on status of TH predictions for simulation of Polarised VBS and experimental techniques

### Conclusions

- Progress in work on templates is promising, but further studies and comparisons are needed
- Potential for MC generators to write out helicity fractions for specific frame was discussed
- Several possibilities to reconstruct $p_z(\nu)$ were mentioned and studied
- Many other issues to discuss
  - choice of frames
  - model independence of measurement
- Much work ahead of us, participants agreed to continue collaborate further

Slide by C. Bittrich

- **Physics objects workshop in Krakow (Oct 2018)**
  https://indico.cern.ch/event/751034/
  Discuss state-of-the art physics object reconstruction in ATLAS/CMS, identify improvements for VBS analyses and possible new techniques (jet reconstruction, ML, …)

### Conclusions and outlook

- Identified many areas where work is needed in order to improve the precision of VBS results
- Both object reco expert and analysis workpower is very welcome in VBScan community
- During a follow-up meeting on Tuesday we discussed possible people involvement in these projects:
  - ~2 groups are interested in polarisation tagging in the VBS-related analyses
  - ATLAS jet/Etmiss group to define projects related to pileup, appropriate for qualification tasks or student projects
  - ongoing works in polarisation tagging of W in WVS and WZ production (semi-leptonic and fully leptonic final states) using MC simulations (Phantom and Madgraph)
- Please let us know if you are interested in contributing to these efforts!!!

Slide by M. Slawinska

# Publications

1) The CLIC Potential for New Physics.
By J. de Blas et al..
[arXiv:1812.02093 [hep-ph]].

2) Heavy resonances and the electroweak effective theory.
By Ignasi Rosell et al..
[arXiv:1811.10233 [hep-ph]].

3) Collider phenomenology of vector resonances in WZ scattering processes.
By Rafael L. Delgado et al..
[arXiv:1811.08720 [hep-ph]].

4) Colorful Imprints of Heavy States in the Electroweak Effective Theory.
By Claudius Krause et al..
[arXiv:1810.10544 [hep-ph]].

5) Studies of Dimension-Six EFT effects in Vector Boson Scattering.
By Raquel Gomez-Ambrosio.
[arXiv:1809.04189 [hep-ph]].

6) Vector Boson Scattering Studies in CMS: The $pp \to ZZ jj$ Channel.
By Raquel Gomez-Ambrosio.
[arXiv:1807.09634 [hep-ph]].
10.5506/APhysPolBSupp.11.239.
Acta Phys.Polon.Supp. 11 (2018) 239-248.

7) Transversal Modes and Higgs Bosons in Electroweak Vector-Boson Scattering at the LHC.
By Simon Brass et al..
[arXiv:1807.02512 [hep-ph]].
10.1140/epjc/s10052-018-6398-4.
Eur.Phys.J. C78 (2018) no.11, 931.

8) Precise predictions for same-sign W-boson scattering at the LHC.
By Alessandro Ballestrero et al..
[arXiv:1803.07943 [hep-ph]].
10.1140/epjc/s10052-018-6136-y.
Eur.Phys.J. C78 (2018) no.8, 671.

9) Stress testing the vector-boson-fusion approximation in multijet final states.
By Francisco Campanario et al..
[arXiv:1802.09955 [hep-ph]].
10.1103/PhysRevD.98.033003.
Phys.Rev. D98 (2018) no.3, 033003.

10) VBSCan Split 2017 Workshop Summary.
By Christoph Falk Anders et al..
[arXiv:1801.04203 [hep-ph]].

11) Resonant production of Wh and Zh at the LHC.
By Antonio Dobado et al..
[arXiv:1711.10310 [hep-ph]].
10.1007/JHEP03(2018)159.
JHEP 1803 (2018) 159.

12) $W$ boson polarization in vector boson scattering at the LHC.
By Alessandro Ballestrero et al..
[arXiv:1710.09339 [hep-ph]].
10.1007/JHEP03(2018)170.
JHEP 1803 (2018) 170.

# Precise predictions for same-sign W-boson scattering at the LHC

arXiv:1803.07943

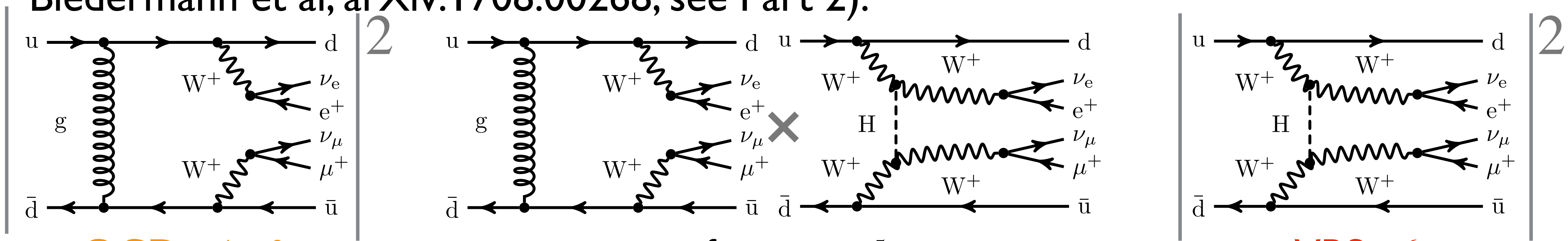
Alessandro Ballestrero, Benedikt Biedermann, Simon Brass, Ansgar Denner, Stefan Dittmaier, Rikkert Frederix, Pietro Govoni, Michele Grossi, Barbara Jager, Alexander Karlberg, Ezio Maina, Mathieu Pellen, Giovanni Pellicciol, Simon Platzer, Michael Rauch, Daniela Rebuzzi, Jurgen Reuter, Vincent Rothe, Christopher Schwan, Hua-Sheng Shao, Pascal Stienemeier, Giulia Zanderighi, MZ, Dieter Zeppenfeld

# Objectives

- Compare the various approximations employed in computer codes, in the VBS fiducial region and in a more inclusive phase space
- Assess the effect of higher-order (NLO) QCD corrections on these approximations
- Analyse how the matching to parton showers and the underlying details affect the results
- Use same-sign $W^+$ production as a case study. Qualitative features similar in other VBS processes.

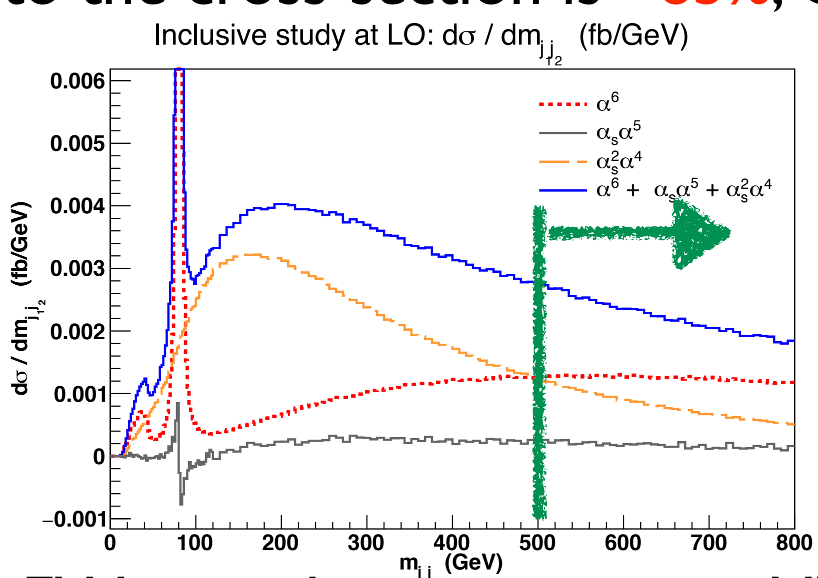
# $e^+\mu^+\nu\nu jj$ production

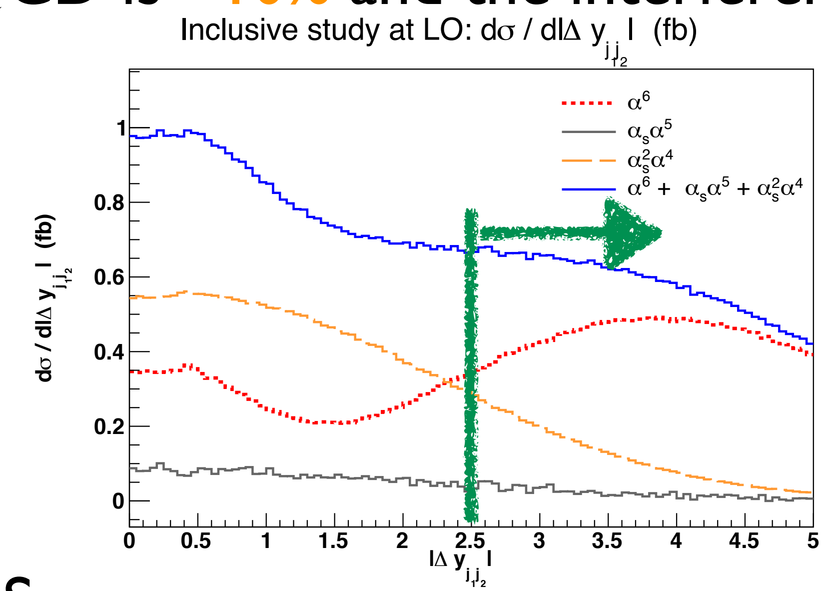
- $W^+W^+jj$ has three coupling combinations at LO, four at NLO (all computed in Biedermann et al, arXiv:1708.00268, see Part 2):




QCD $\alpha^4\alpha_s^2$ interference $\alpha^5\alpha_s$ VBS $\alpha^6$

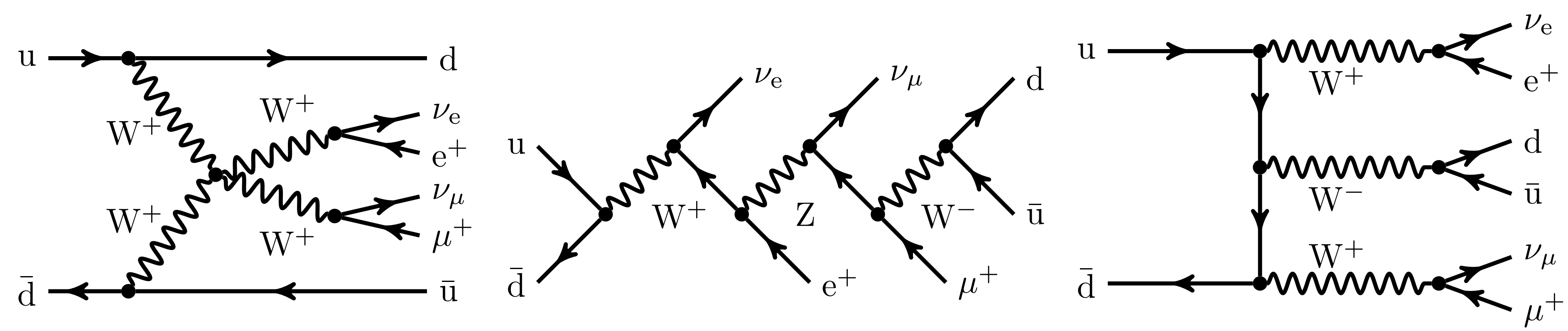
- The vector-boson scattering (VBS) contribution is typically considered the signal, while the QCD-induced is a background
- Within typical VBS cuts (large dijet invariant mass and rapidity separation), at LO the EW contribution to the cross-section is ~85%, QCD is ~10% and the interference is very small (<5%)




- However, the EW contribution is not just VBS…

# Anatomy of the EW contribution




- Besides diagrams involving VBS, tri-boson production and diagrams with off-shell bosons also lead to the same final-state
- After VBS cuts, the latter two contributions are strongly suppressed
- Approaches employed in different codes vary from being pragmatic (just including VBS-like, i.e. t/u channel diagrams) to being very rigorous (include everything)

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

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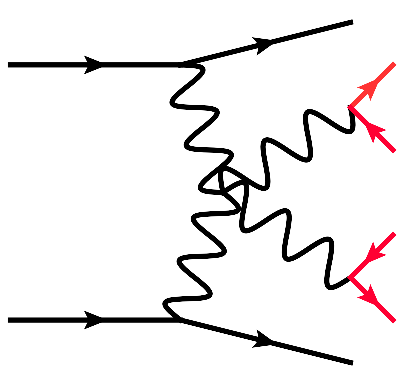
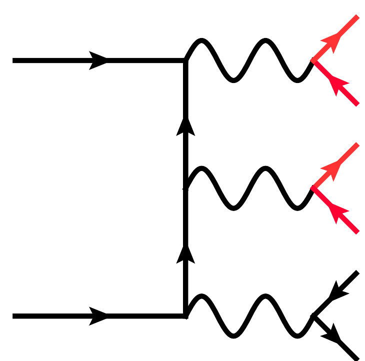
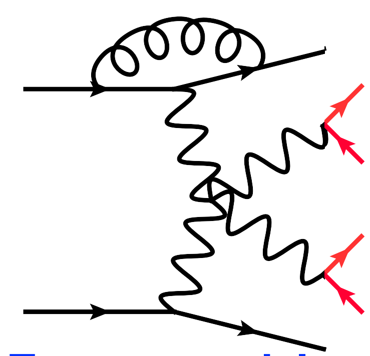
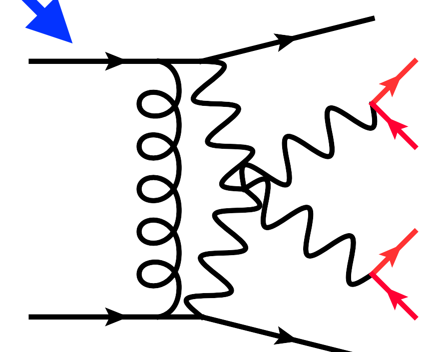
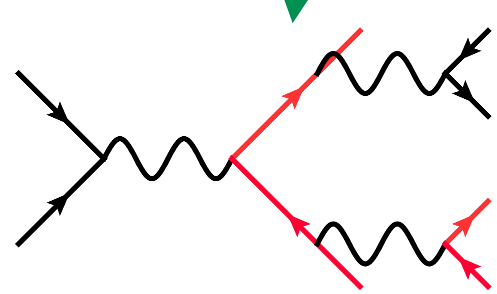

t-channel


s-channel


Factorizable QCD corr.


Non-Factorizable QCD corr.


Off-shell and non resonant

# Setup, cuts and parameters

- Couplings, masses and widths

$$G_\mu = 1.16637 \times 10^{-5}\,\text{GeV}$$

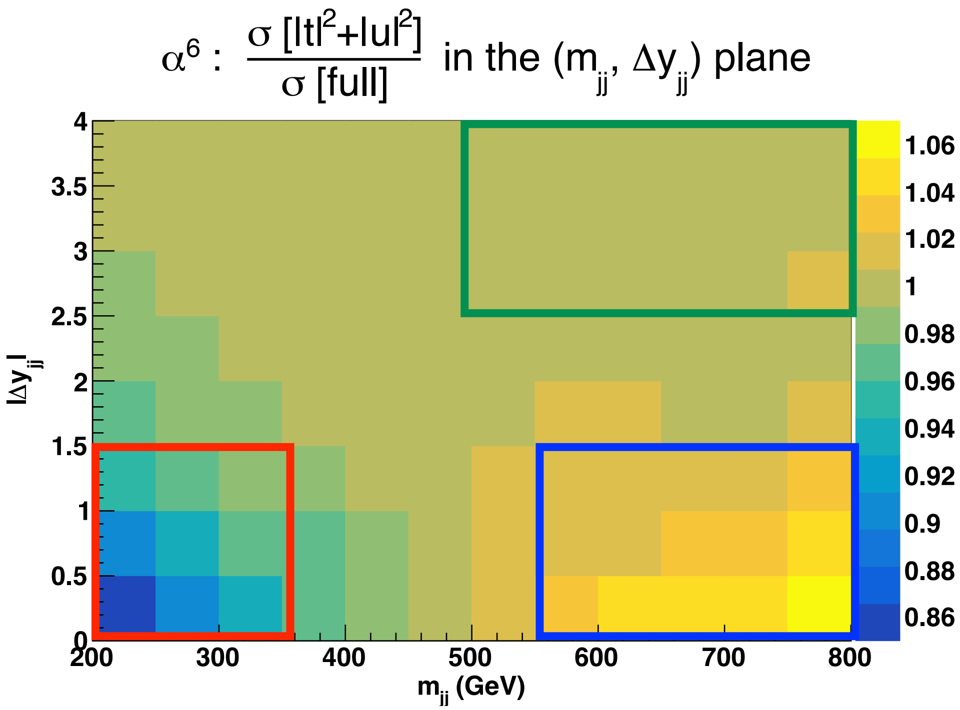
$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right)$$

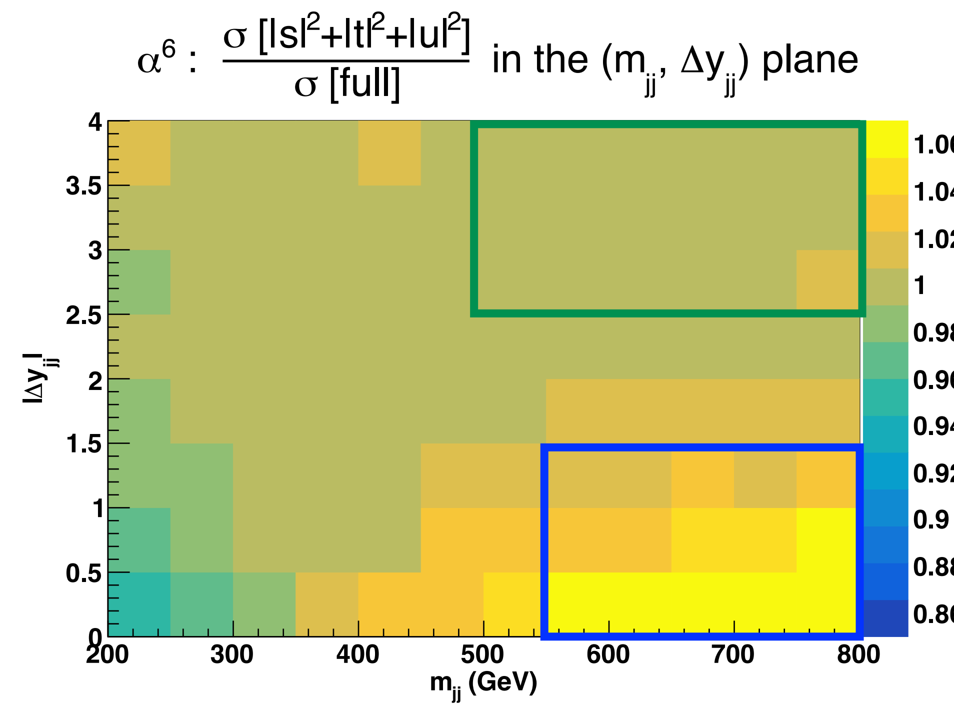
$$\begin{aligned} m_t &= 173.21\,\text{GeV}, & \Gamma_t &= 0\,\text{GeV}, \\ M_Z^{OS} &= 91.1876\,\text{GeV}, & \Gamma_Z^{OS} &= 2.4952\,\text{GeV}, \\ M_W^{OS} &= 80.385\,\text{GeV}, & \Gamma_W^{OS} &= 2.085\,\text{GeV}, \\ M_H &= 125.0\,\text{GeV}, & \Gamma_H &= 4.07 \times 10^{-3}\,\text{GeV} \end{aligned}$$

- NNPDF 3.0 PDFs, $\alpha_s(M_Z)$=0.118, $\mu^2_{R/F}=p_T(j_1) \cdot p_T(j_2)$
- Selection cuts:
  - At least two (anti-$k_T$,R=0.4) jets with $p_T$>30 GeV, |y|<4.5, with jet-lepton distance $\Delta R_{jl}$>0.3
  - The two hardest jet must have $\Delta y$>2.5, $m_{jj}$>500 GeV
  - Two leptons with $p_T$>20 GeV, |y|<2.5, $E_T^{miss}$>40 GeV
  - Lepton-lepton distance: $\Delta R_{ll}$>0.3

# VBS approximation vs. full computation

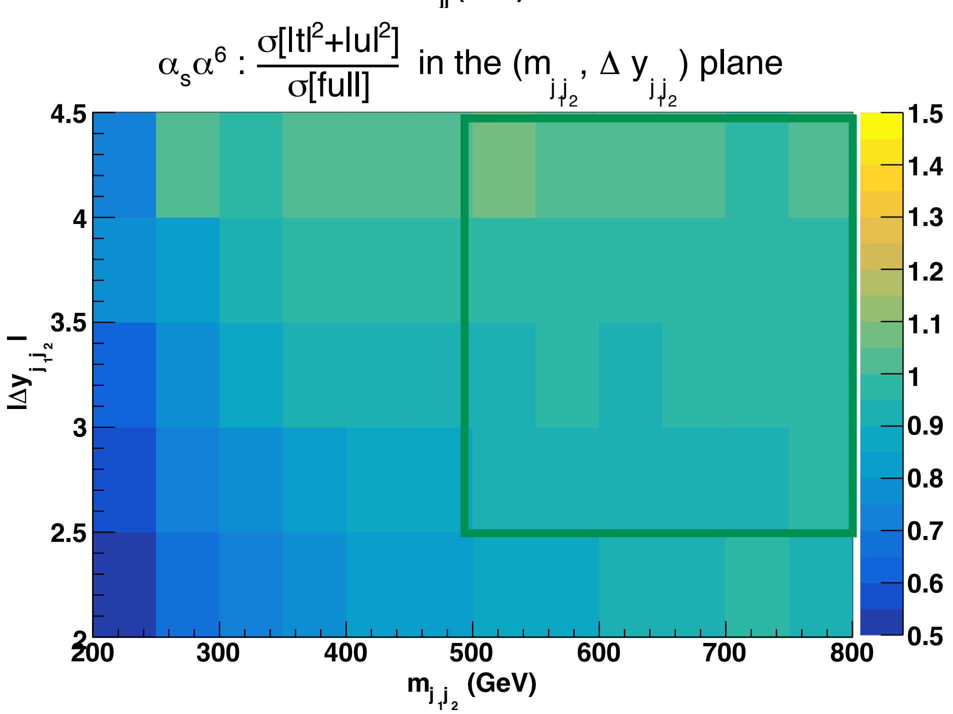
LO

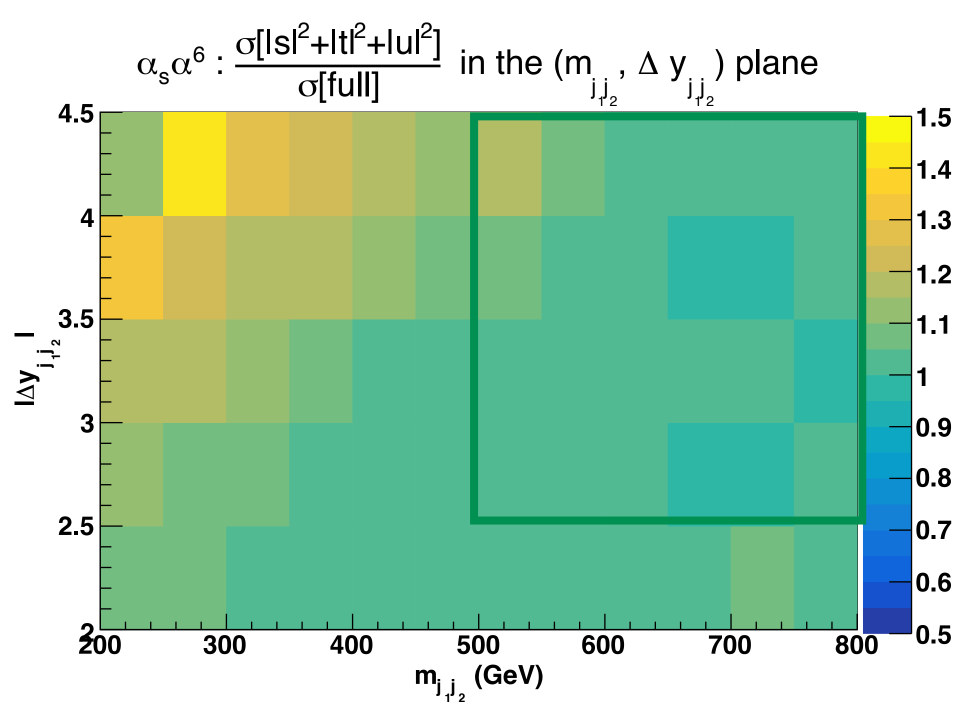


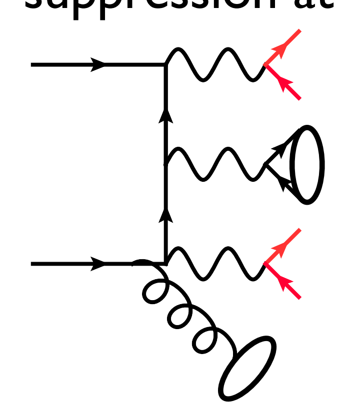

- Very small differences at LO in the VBF-selection region
- s-channel (triboson) contribution mostly at low $m_{jj}$-$\Delta y_{jj}$
- interference visible at large $m_{jj}$- low $\Delta y_{jj}$

NLO

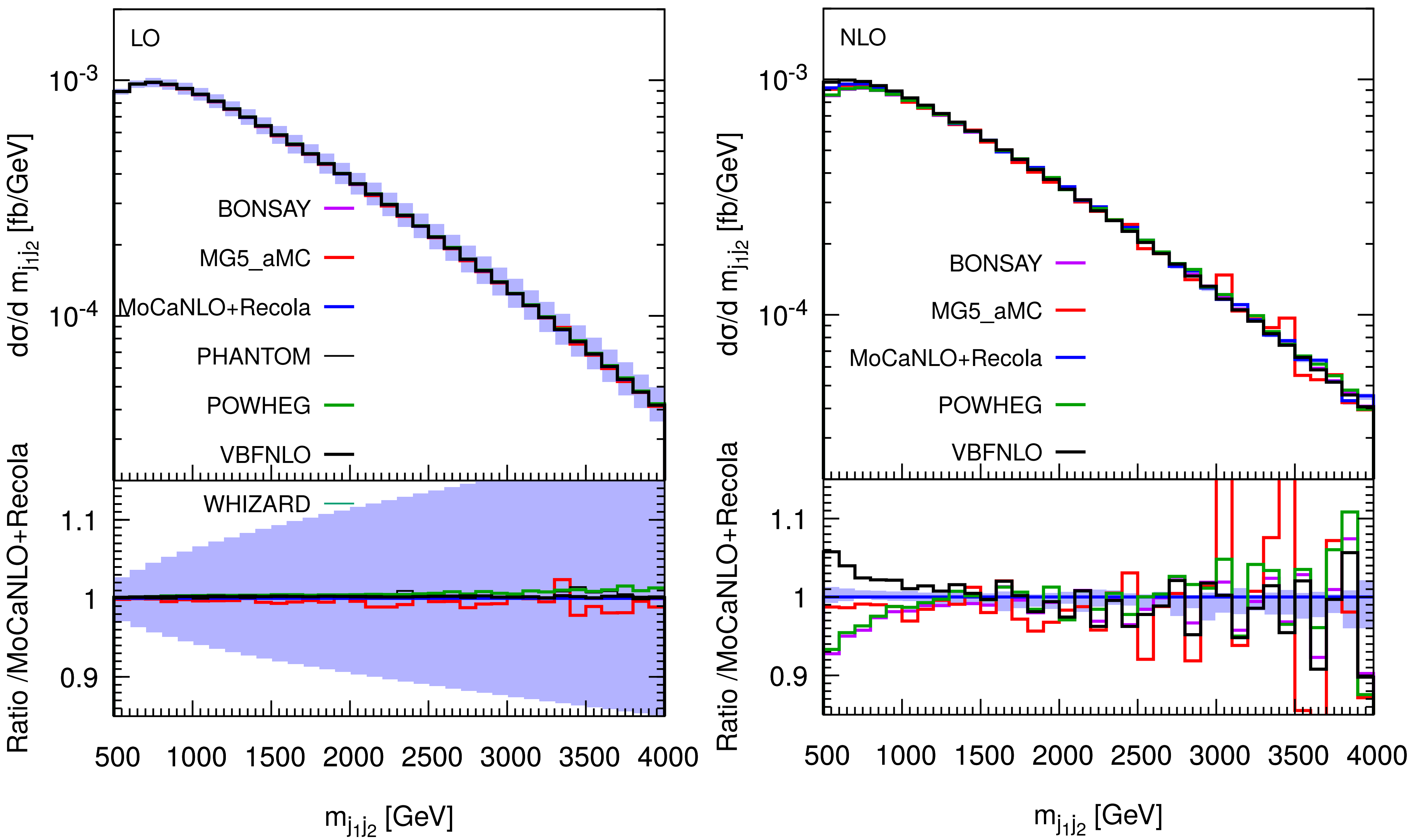



- At NLO, the impact of s-channel contribution, even in the VBF-selection region, is larger
- Extra radiation reduces suppression at large $m_{jj}$

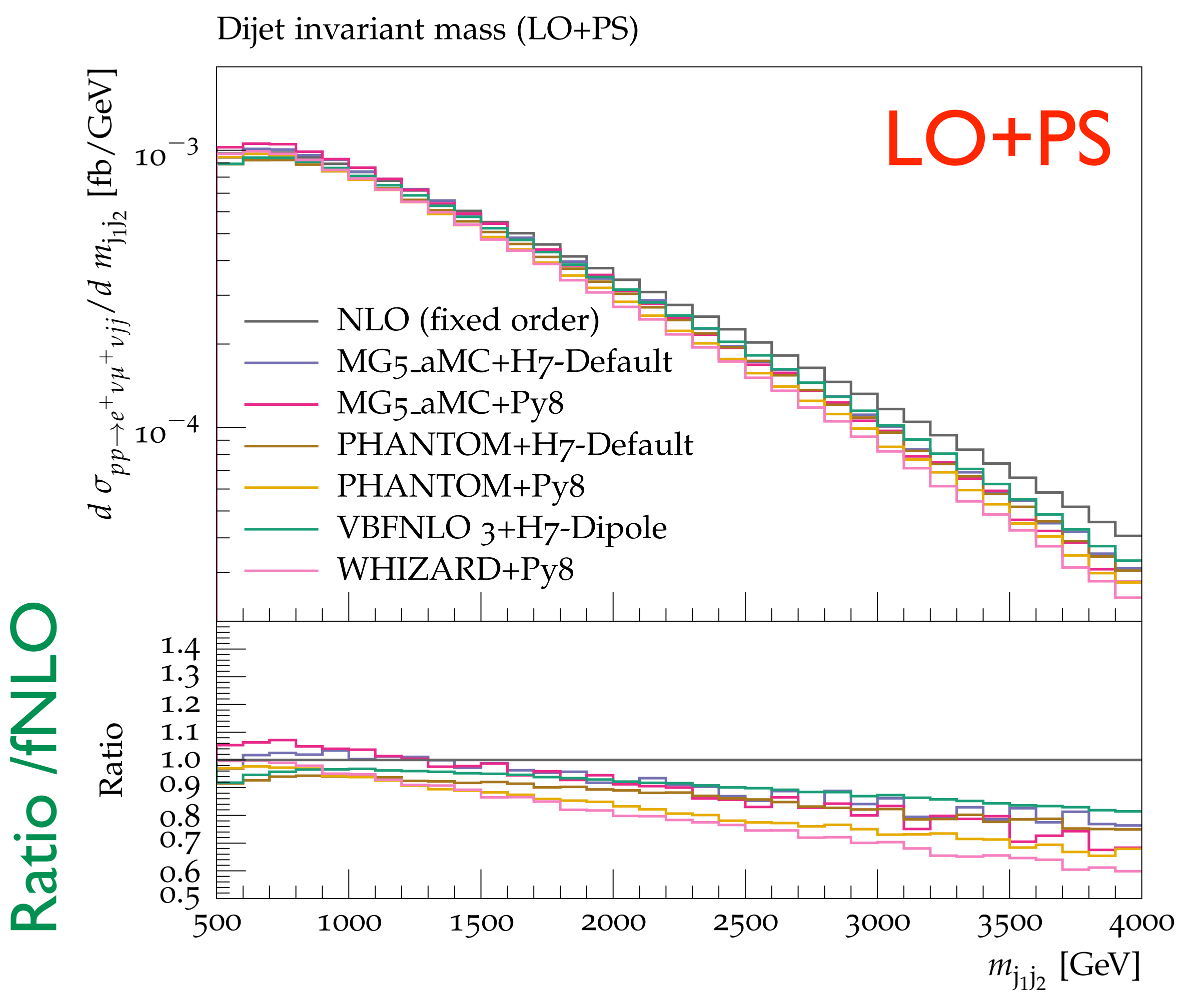


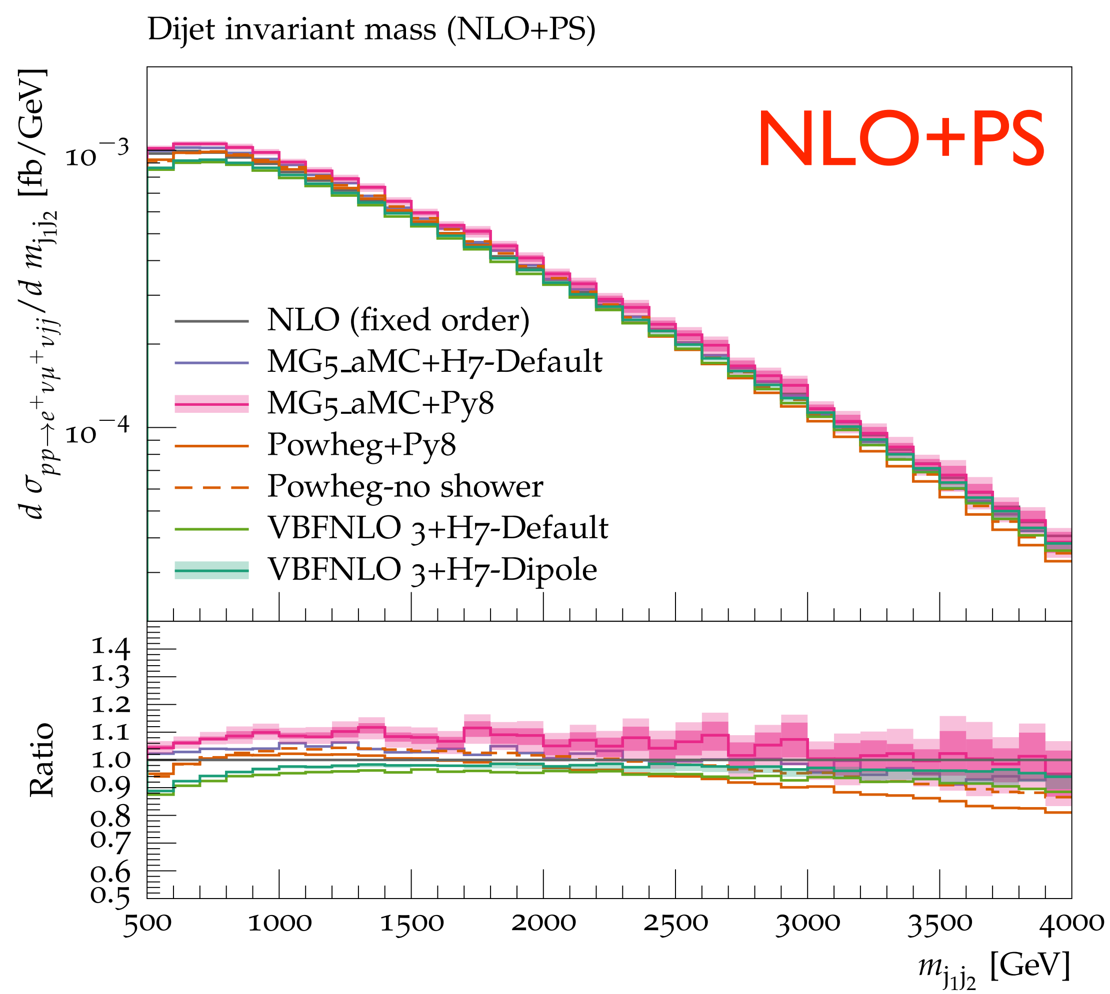
# Comparison of codes at fixed-order




- Baseline for comparison is MoCaNLO+Recola, most complete computation at LO and NLO (with scale-uncertainty band)
- Different approximations give identical results at LO, within VBS cuts
- Larger differences (still below 10%) appear at NLO:
  - Powheg and Bonsay do not include tri-boson contributions → suppression at small $m_{jj}$
  - VBFNLO includes tri-boson, but not the interference → enhancement at small $m_{jj}$

# Matching to parton shower: $m_{jj}$

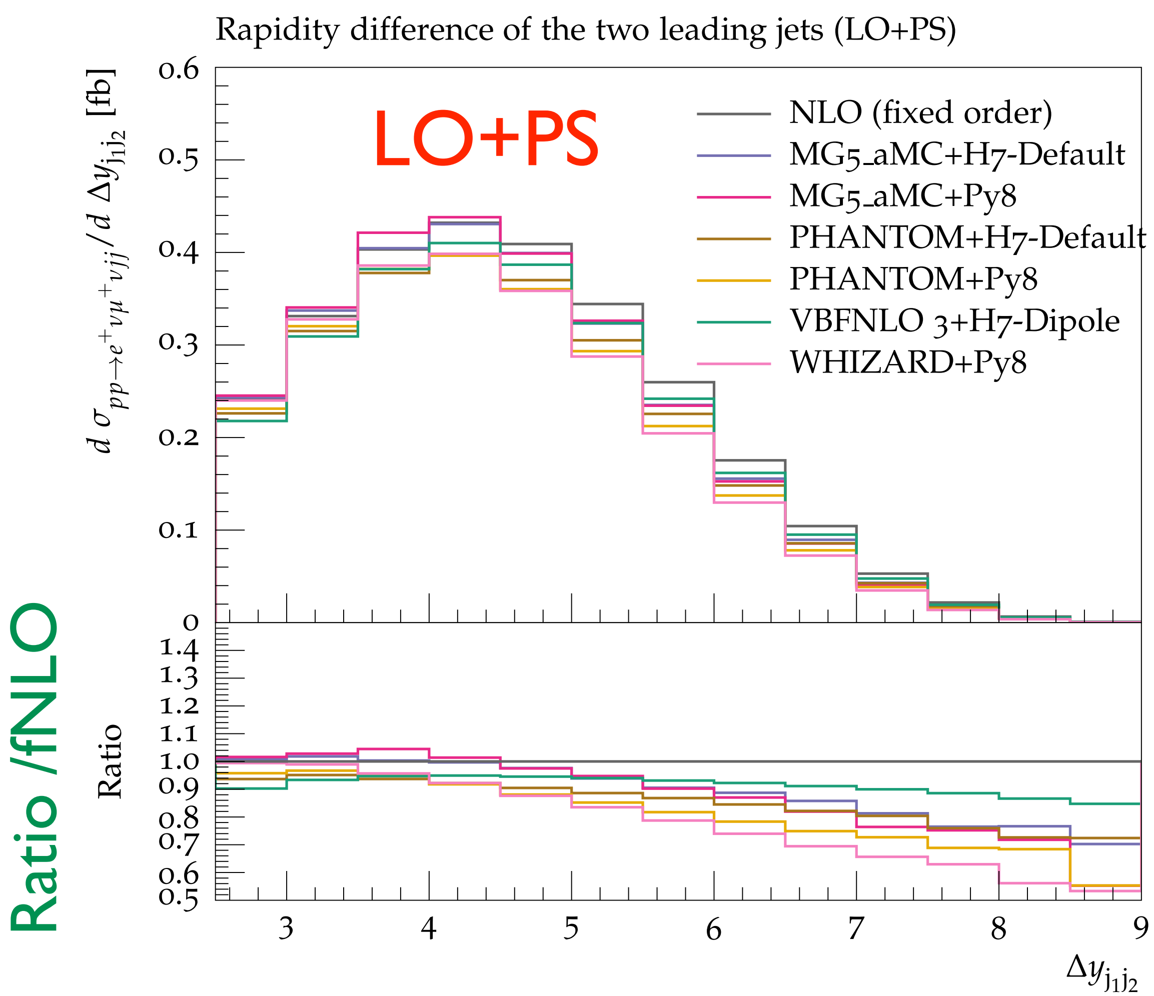


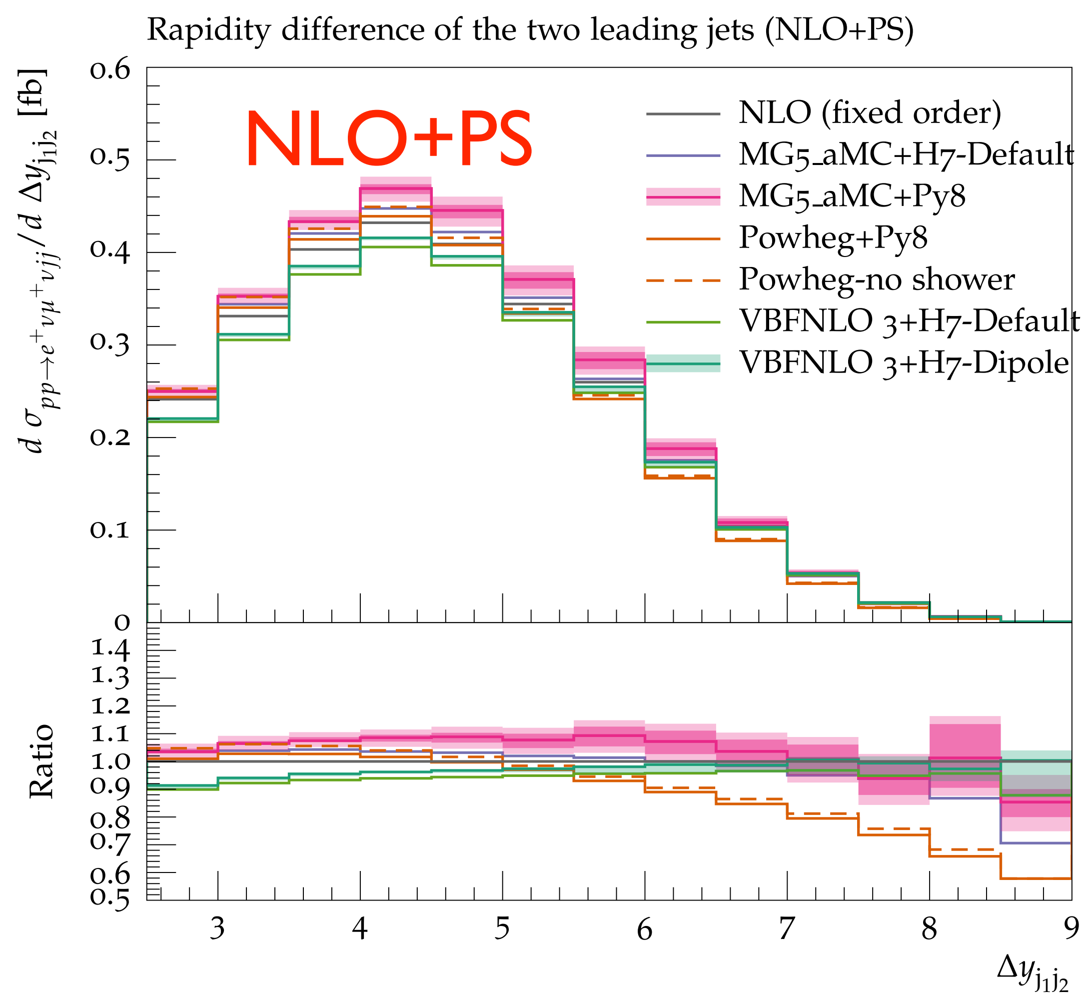




- The inclusion of NLO corrections improve the description of the extra radiation at large $m_{jj}$ (undershot by LOPS)

- Scale and PDF uncertainties are not representative of spread of different predictions
- For NLO-accurate observables, NLOPS predictions typically lie within ±10% (an exception in the next slide)

# Matching to parton shower: $\Delta y_{jj}$

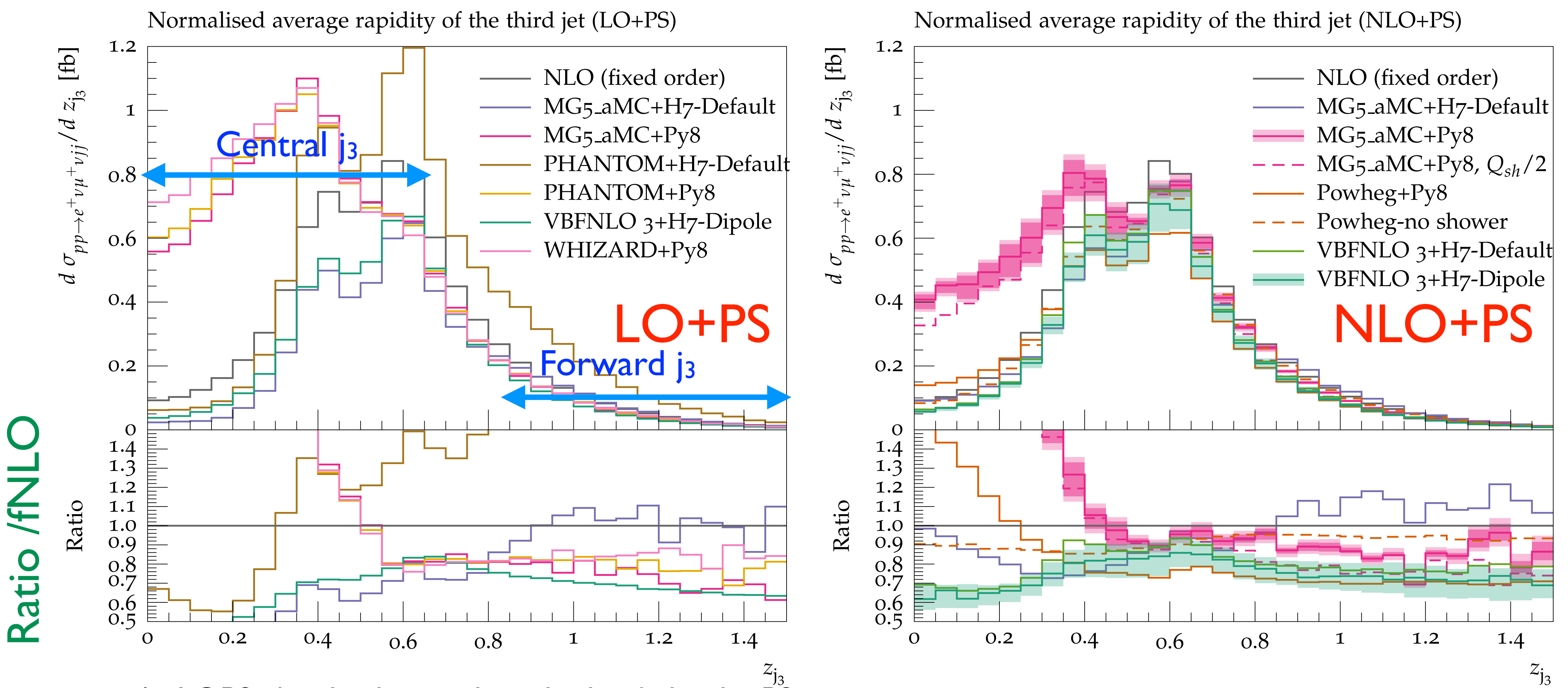



- The inclusion of NLO corrections improve the description of the extra radiation at large $m_{jj}$ (undershot by LOPS)
- Powheg predictions show a suppression at large $\Delta y_{jj}$, due to the Powheg handling of the first radiation (internal Sudakov factor)

# Matching to parton shower:

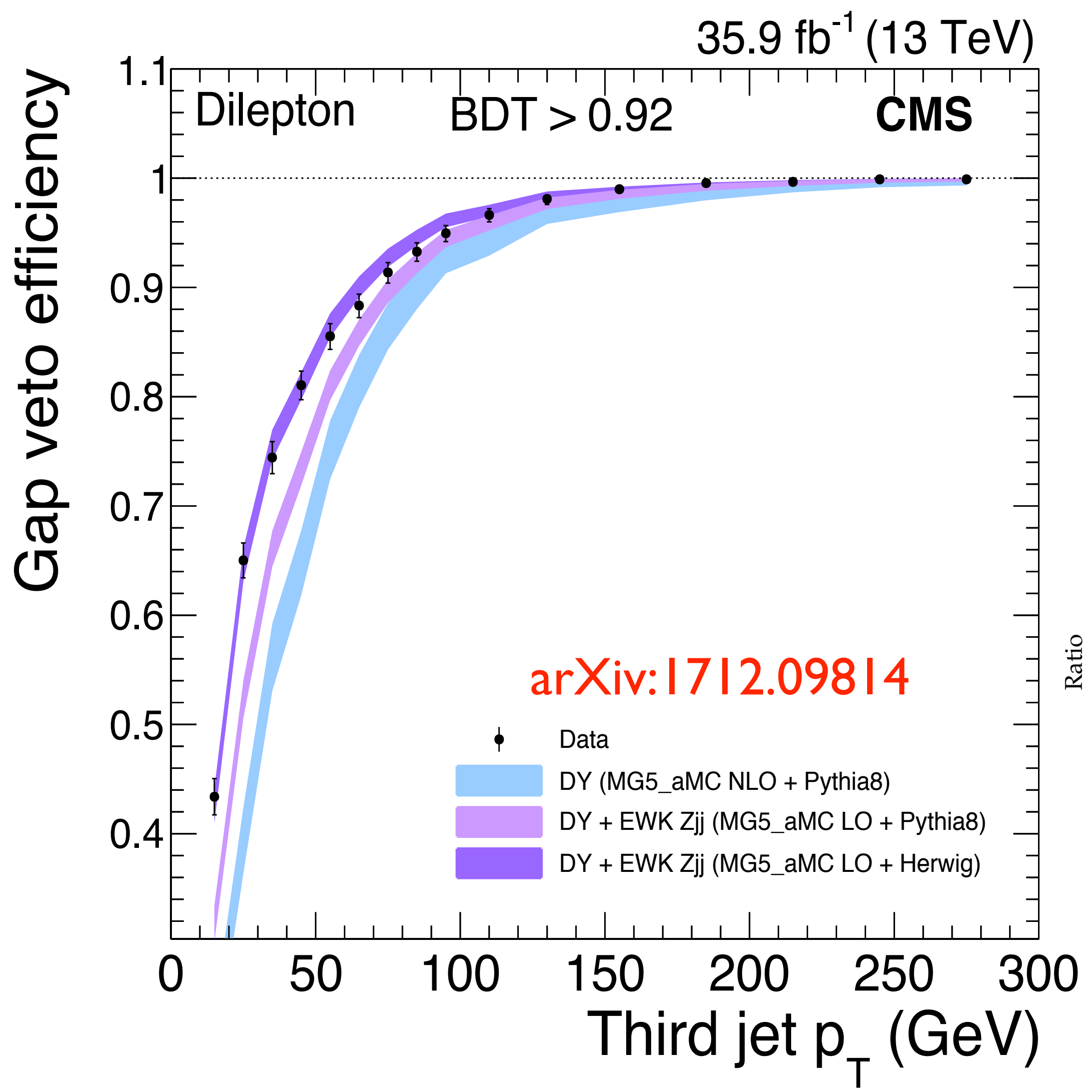
$$z_3 = \frac{y_3 - (y_1 + y_2)/2}{|\Delta y_{jj}|}$$




- At LOPS, the third jet is described only by the PS → Very large differences among tools
- PY8 gives large enhancement in the central region. Unphysical effect due to not-so accurate treatment of initial-final color connections. Can be cured with `SpaceShower:dipoleRecoil=on` (version≥8.230)

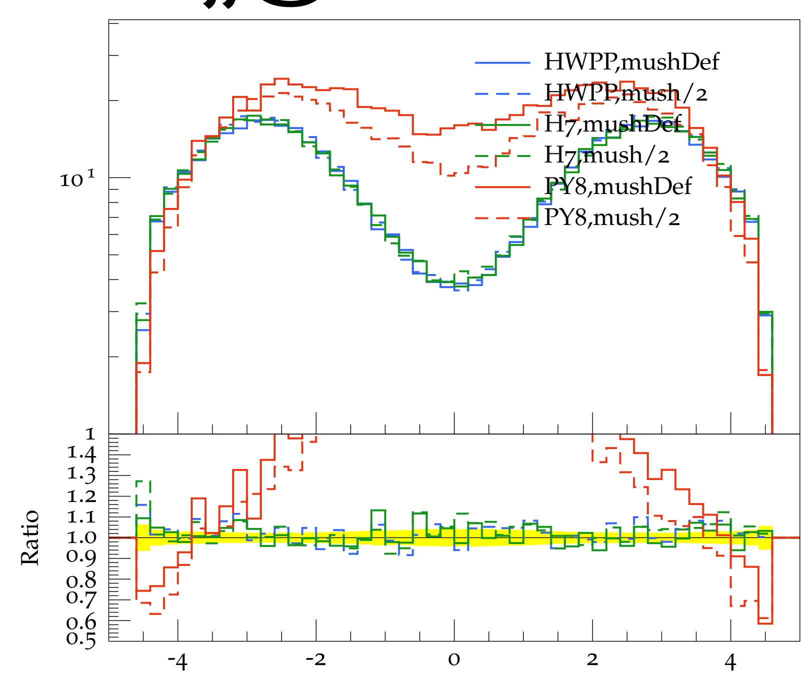
- Central enhancement by PY8 survives also at NLO, although somehow reduced
- Smaller effect in Powheg, because of the treatment of the 1st emission
- Note that `dipoleRecoil=on` is not compatible with MC@NLO-type matching as implemented in MG5_aMC
- Besides PY8, differences remain much larger than for NLO-accurate observables

# Central j3 enhancement in PY8

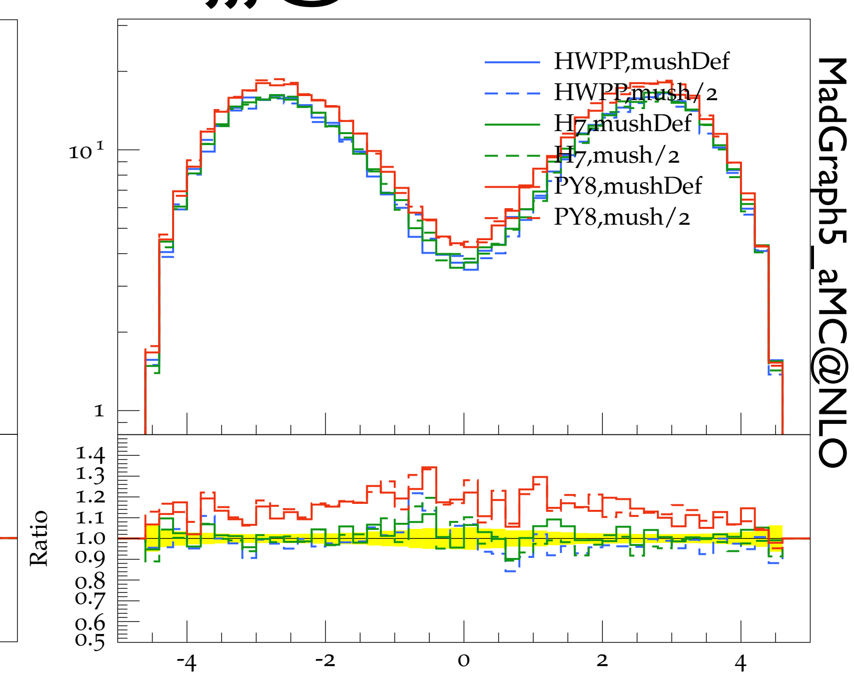



- Same feature observed for similar processes, e.g. Zjj production in VBF or Higgs VBF production

## Hjj@NLO in VBF




## Hjjj@NLO in VBF




- Reduction of shower scale (dashed) only partly compensates central enhancement
- A NLO description of j3 greatly reduces the effect (may be feasible also for VBS)

# Conclusions

**VBSCan**

- The VBSCan community is highly committed to improve our understanding of VBS processes
- Everybody can join and take part to VBSCan activities! VBSCan can provide support
- Lot of possible synergies with the EWWG: close collaboration is foreseen

**Precise predictions for same-sign W-boson scattering at the LHC**

- Various approximations employed for VBS processes have been thoroughly compared and validated
- VBS approximation works quite well (within 10% from the full compuation at NLO) with typical VBS cuts. For more inclusive setups, a complete computation is better suited
- NLO+PS tools are available, with good overall agreement for NLO-accurate observables. Note however that scale (and PDF) uncertainties are not representative of the spread of predictions
- Larger discrepancies appear for observables related to $j_3$. The most pronounced ones are due to the recoil scheme in Pythia8