Precise predictions for VBS: Montecarlo simulations and Electroweak corrections

Marco Zaro

Multi-Boson Interactions 2018

Outline:

- Part 1: MC generators and different approximations in VBS
- Part 2: Electro-Weak corrections in VBS
- Part 3: Electro-Weak corrections to multi-boson production

Part 1:
MC generators and different approximations in VBS

arXiv:1803.07943

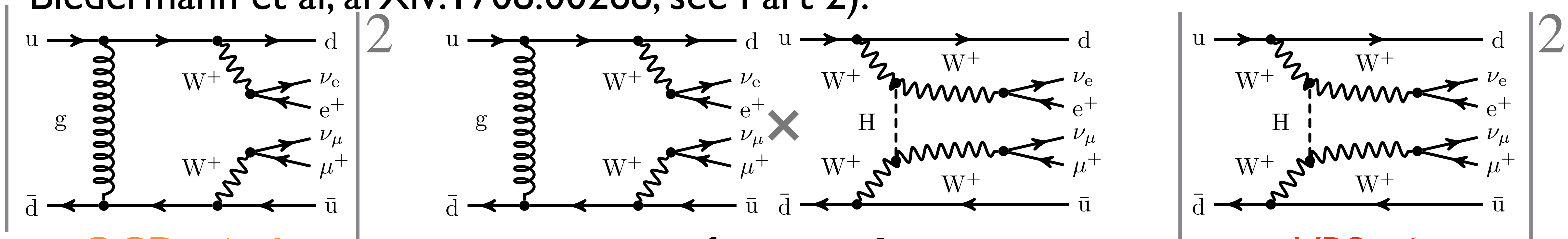
Alessandro Ballestrero, Benedikt Biedermann, Simon Brass, Ansgar Denner, Stefan Dittmaier, Rikkert Frederix, Pietro Govoni, Michele Grossi, Barbara Jager, Alexander Karlberg, Ezio Maina, Mathieu Pellen, Giovanni Pelliccioli, Simon Platzer, Michael Rauch, Daniela Rebuzzi, Jurgen Reuter, Vincent Rothe,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

Objectives

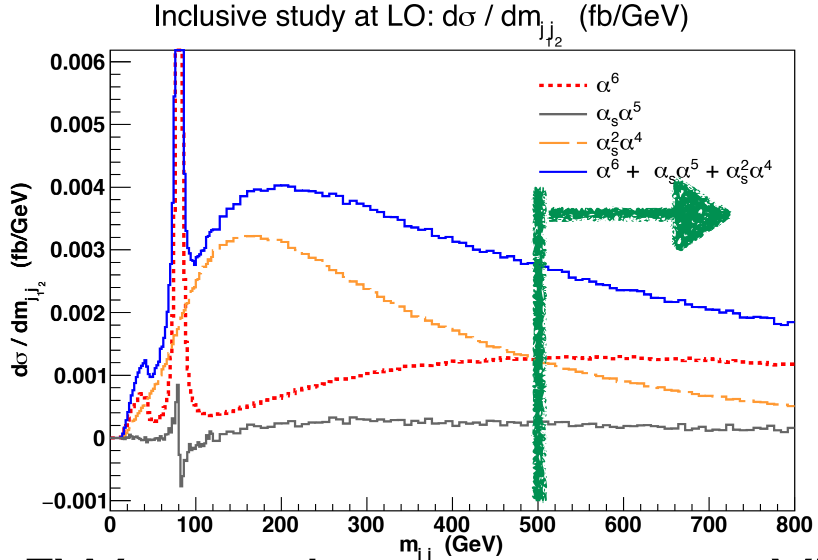
- Compare the various approximations employed in computer codes, in the VBS fiducial region and in a more inclusive phase space
- Assess the effect of higher-order (NLO) QCD corrections on these approximations
- Analyse how the matching to parton showers and the underlying details affect the results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

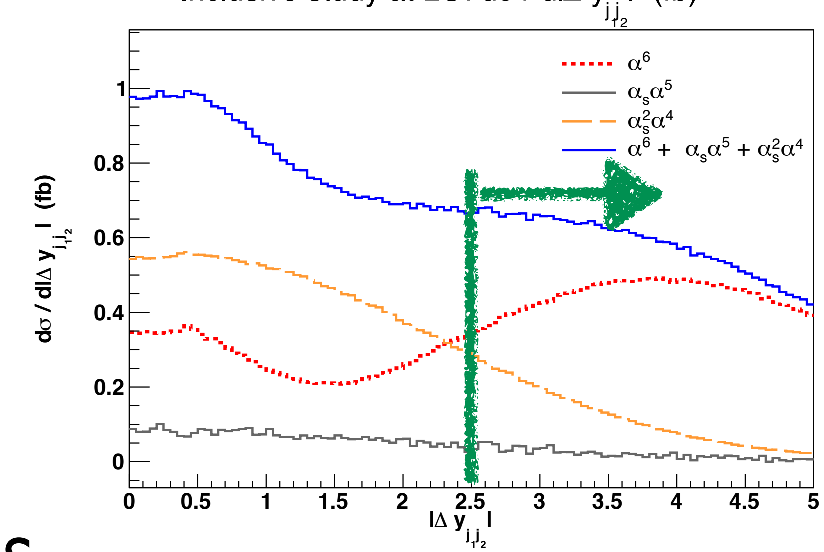
$e^+\mu^+\nu\nu jj$ production

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



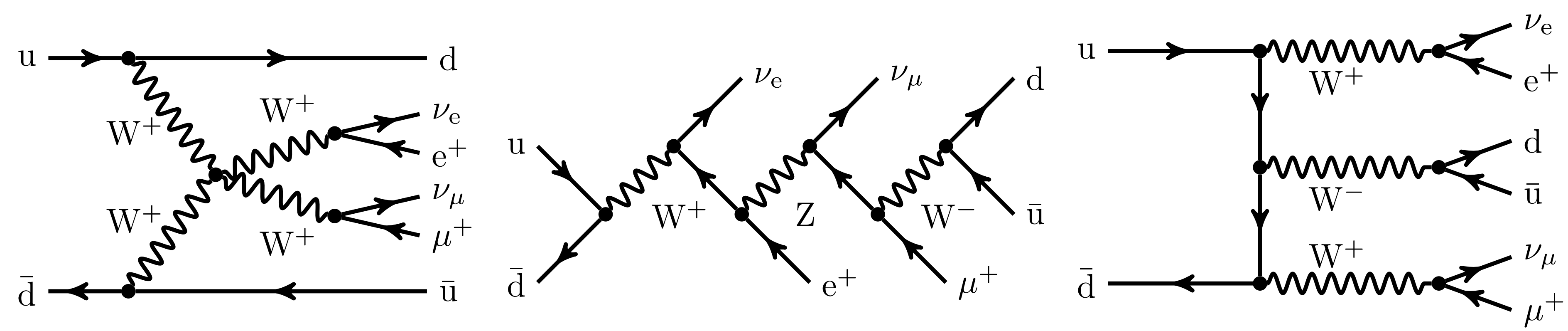
- The vector-boson scattering (VBS) contribution is typically considered the signal, while the QCD-induced is a background
- Within typical VBS cuts (large dijet invariant mass and rapidity separation), at LO the EW contribution to the cross-section is ~85%, QCD is ~10% and the interference is very small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





- However, the EW contribution is not just VBS…

Anatomy of the EW contribution

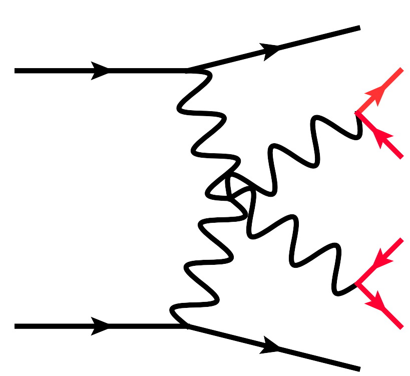


- Besides diagrams involving VBS, tri-boson production and diagrams with off-shell bosons also lead to the same final-state
- After VBS cuts, the latter two contributions are strongly suppressed
- Approaches employed in different codes vary from being pragmatic (just including VBS-like, i.e. t/u channel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

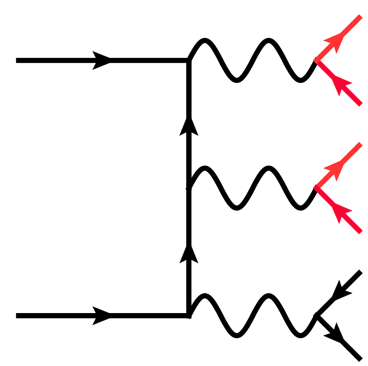
Code	$\mathcal{O}(\alpha^6)$ s,t,u	$\mathcal{O}(\alpha^6)$ interf.	Non-res.	NLO	NF QCD	EW corr. to order $\mathcal{O}(\alpha_s\alpha^5)$
Bonsay	t,u	No	Yes, virt. No	Yes	No	No
Powheg	t,u	No	Yes	Yes	No	No
MG5_aMC	s,t,u	Yes	Yes	Yes	virt. No	No
MoCaNLO+Recola	s,t,u	Yes	Yes	Yes	Yes	Yes
PHANTOM	s,t,u	Yes	Yes	No	-	-
VBFNLO	s,t,u	No	Yes	Yes	No	No
Whizard	s,t,u	Yes	Yes	No	-	-

Anatomy of the EW contribution

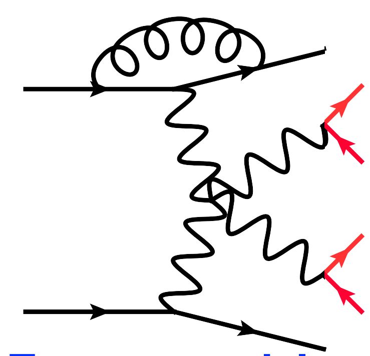
Code	$\mathcal{O}(\alpha^6)$ s,t,u	$\mathcal{O}(\alpha^6)$ interf.	Non-res.	NLO	NF QCD	EW corr. to order $\mathcal{O}(\alpha_s\alpha^5)$
BONSAY	t,u	No	Yes, virt. No	Yes	No	No
POWHEG	t,u	No	Yes	Yes	No	No
MG5_AMC	s,t,u	Yes	Yes	Yes	virt. No	No
MOCANLO+RECOLA	s,t,u	Yes	Yes	Yes	Yes	Yes
PHANTOM	s,t,u	Yes	Yes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



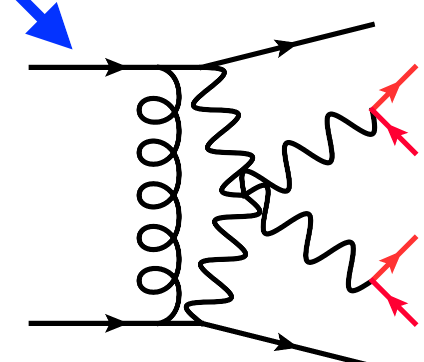
t-channel



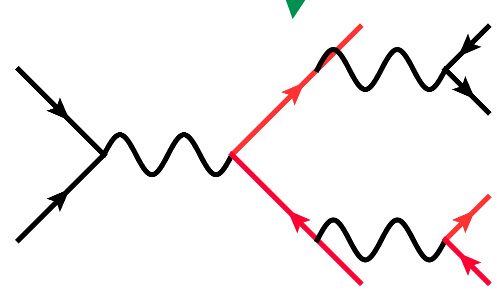
s-channel



Factorizable QCD corr.



Non-Factorizable QCD corr.



Off-shell and non resonant

Setup, cuts and parameters

- Couplings, masses and widths

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

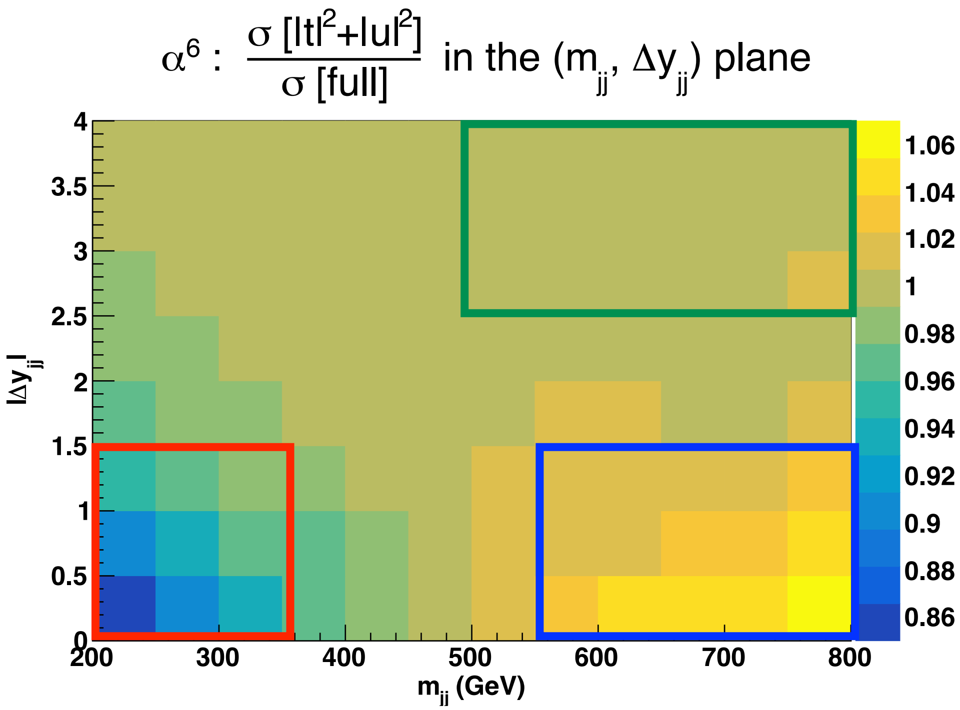
$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right)$$

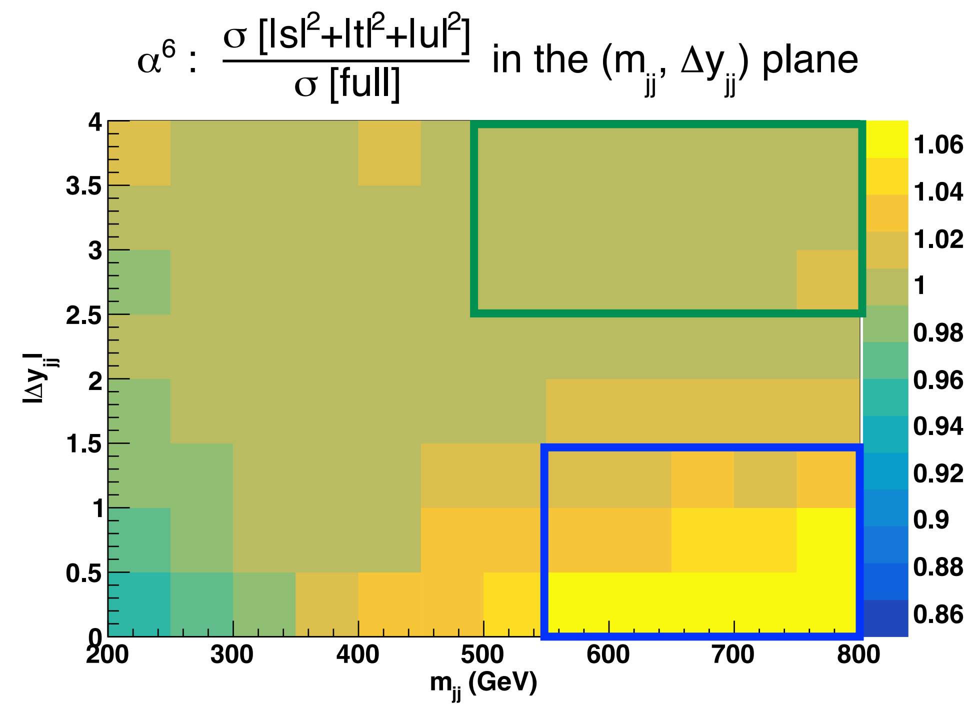
$$\begin{aligned} m_t &= 173.21\,\text{GeV}, & \Gamma_t &= 0\,\text{GeV}, \\ M_Z^{OS} &= 91.1876\,\text{GeV}, & \Gamma_Z^{OS} &= 2.4952\,\text{GeV}, \\ M_W^{OS} &= 80.385\,\text{GeV}, & \Gamma_W^{OS} &= 2.085\,\text{GeV}, \\ M_H &= 125.0\,\text{GeV}, & \Gamma_H &= 4.07 \times 10^{-3}\,\text{GeV} \end{aligned}$$

- 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

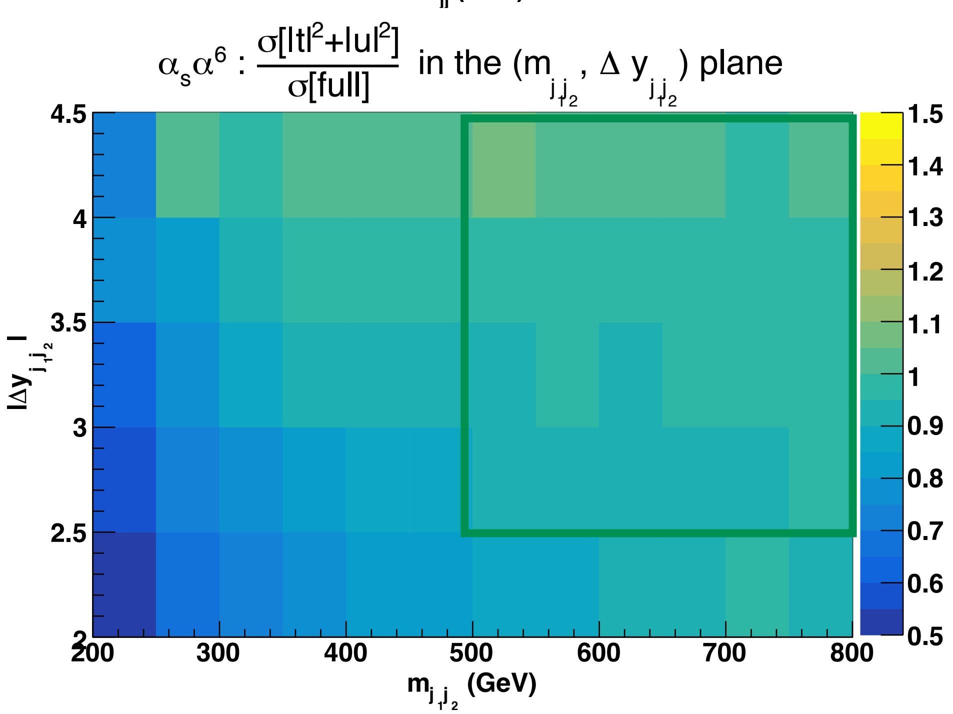
LO

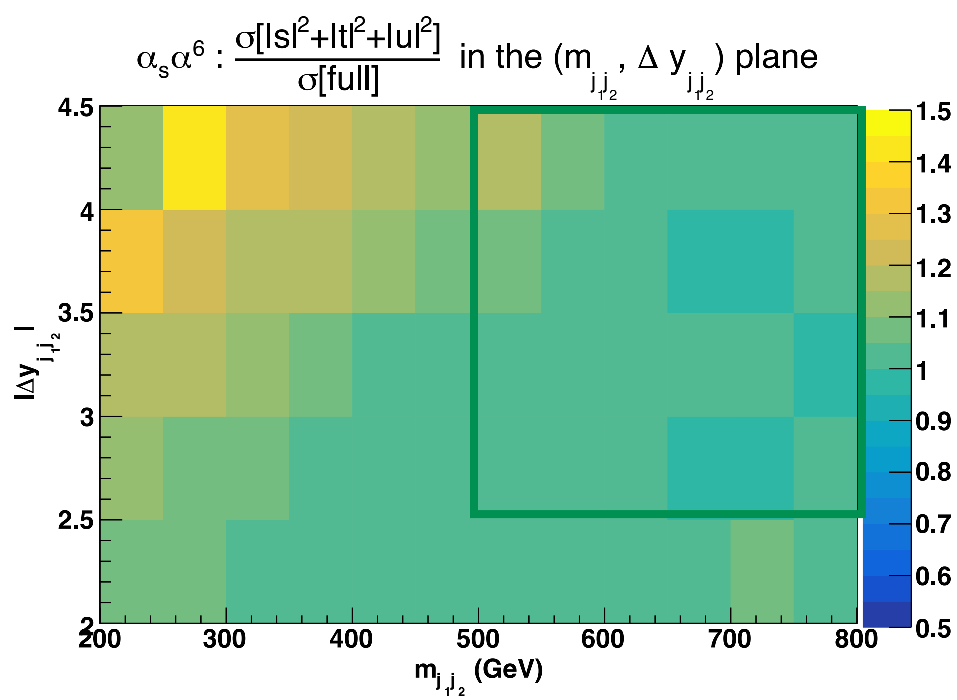




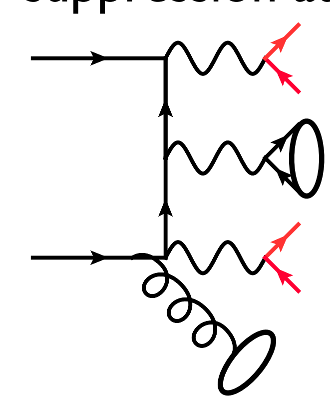
- Very small differences at LO in the VBF-selection region
- s-channel (triboson) contribution mostly at low m_{jj}-Δy_{jj}
- interference visible at large m_{jj}- low Δy_{jj}

NLO

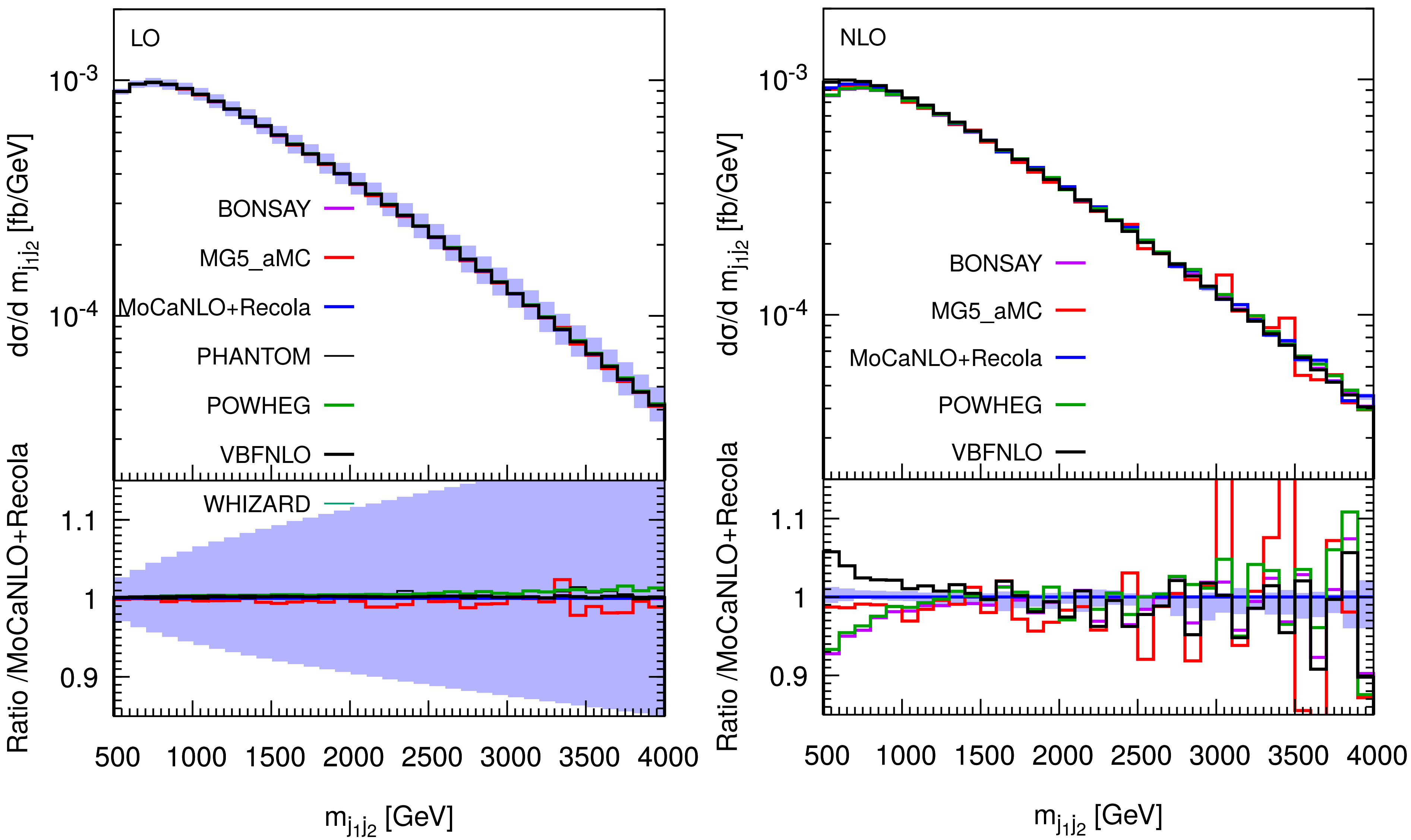




- At NLO, the impact of s-channel contribution, even in the VBF-selection region, is larger
- Extra radiation reduces suppression at large m_{jj}

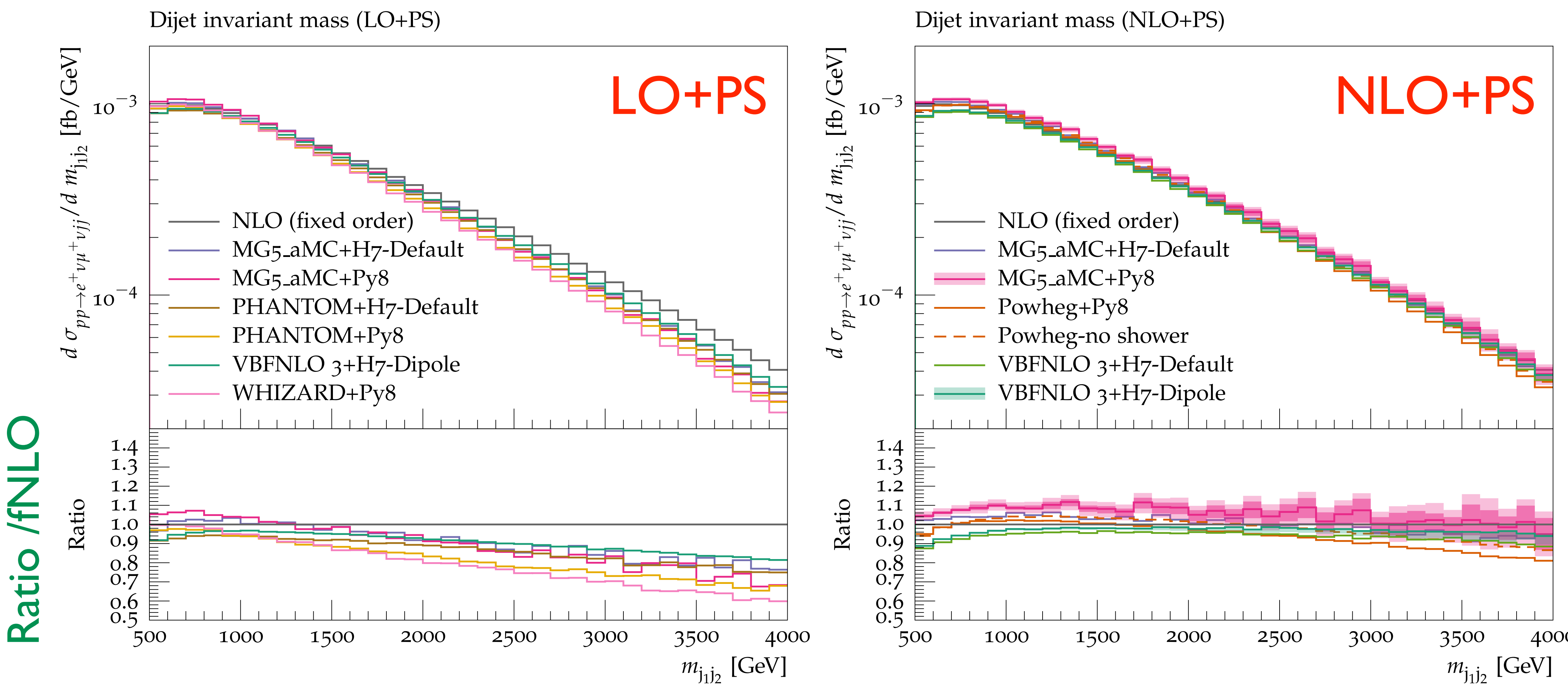


Comparison of codes at fixed-order



- 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}

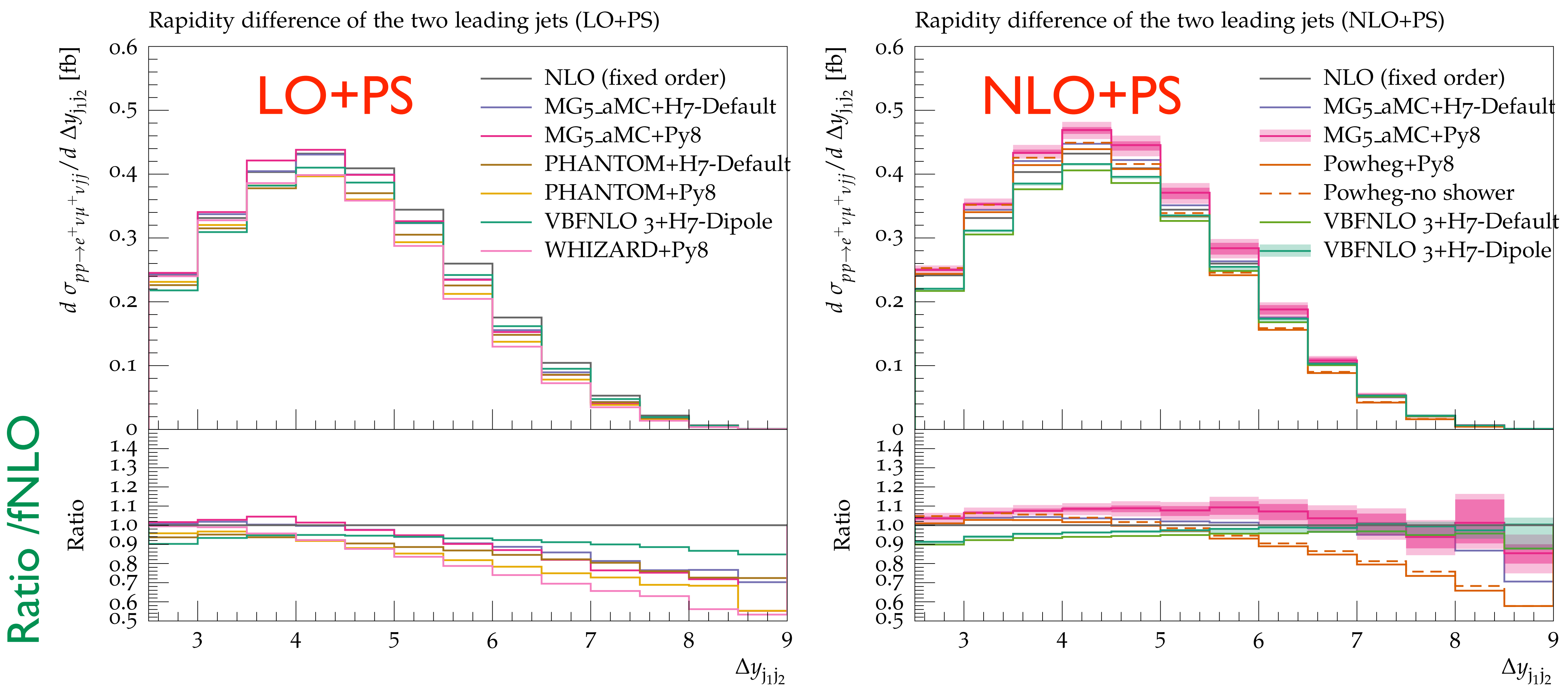
Matching to parton shower: m_{jj}



- 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)

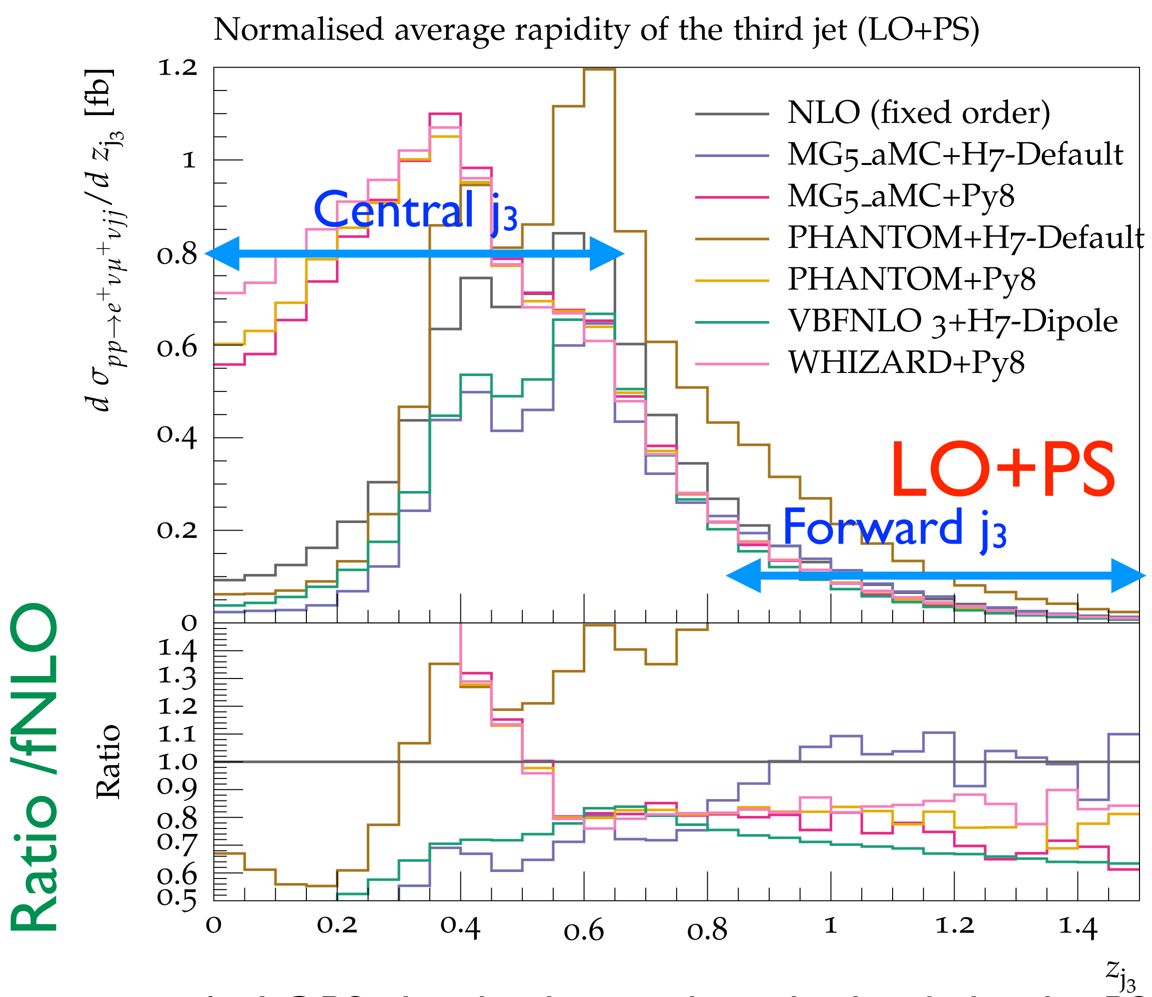
Matching to parton shower: Δy_{jj}

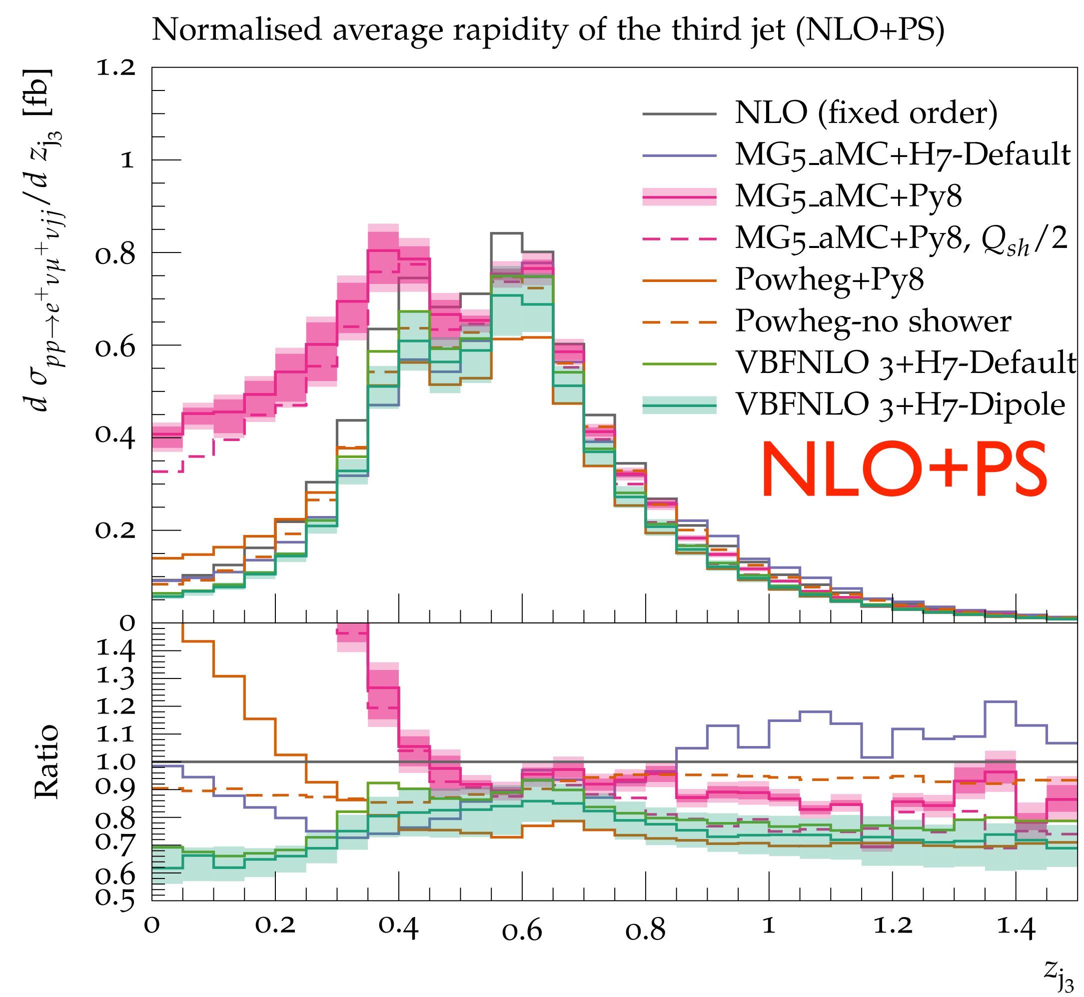


- The inclusion of NLO corrections improve the description of the extra radiation at large m_{jj} (undershot by LOPS)
- Powheg predictions show a suppression at large Δy_{jj}, due to the Powheg handling of the first radiation (internal Sudakov factor)

Matching to parton shower:

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

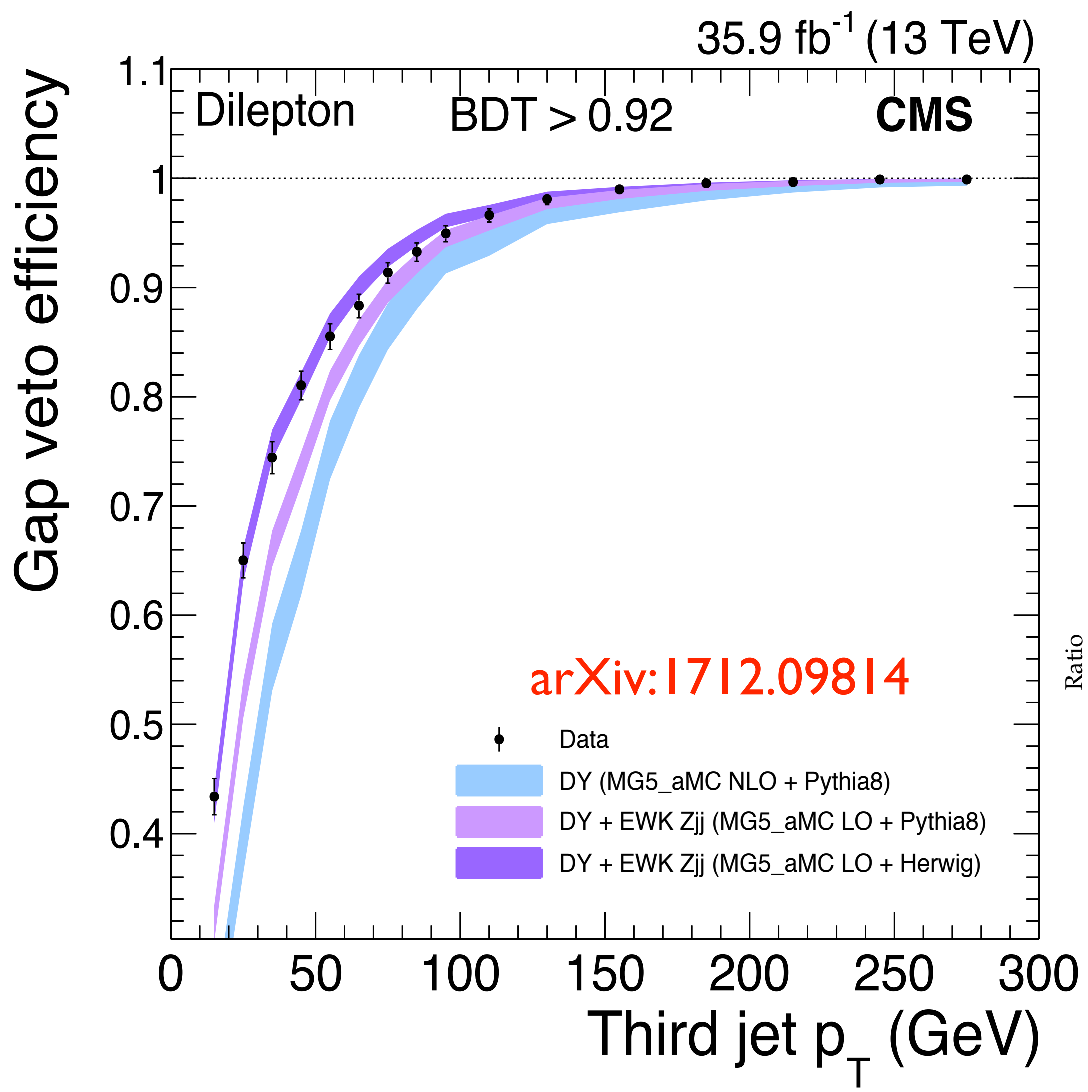




- At LOPS, the third jet is described only by the PS → Very large differences among tools
- PY8 gives large enhancement in the central region. Unphysical effect due to not-so accurate treatment of initial-final color connections. Can be cured with `SpaceShower:dipoleRecoil=on` (version≥8.230)

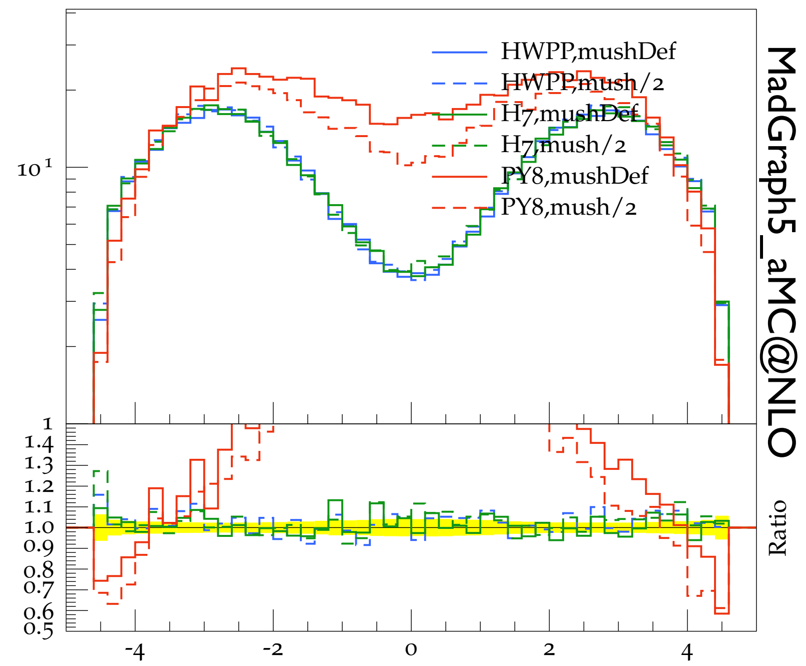
- Central enhancement by PY8 survives also at NLO, although somehow reduced
- Smaller effect in Powheg, because of the treatment of the 1st emission
- Note that `dipoleRecoil=on` is not compatible with MC@NLO-type matching as implemented in MG5_aMC
- Besides PY8, differences remain much larger than for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

Central j3 enhancement in PY8

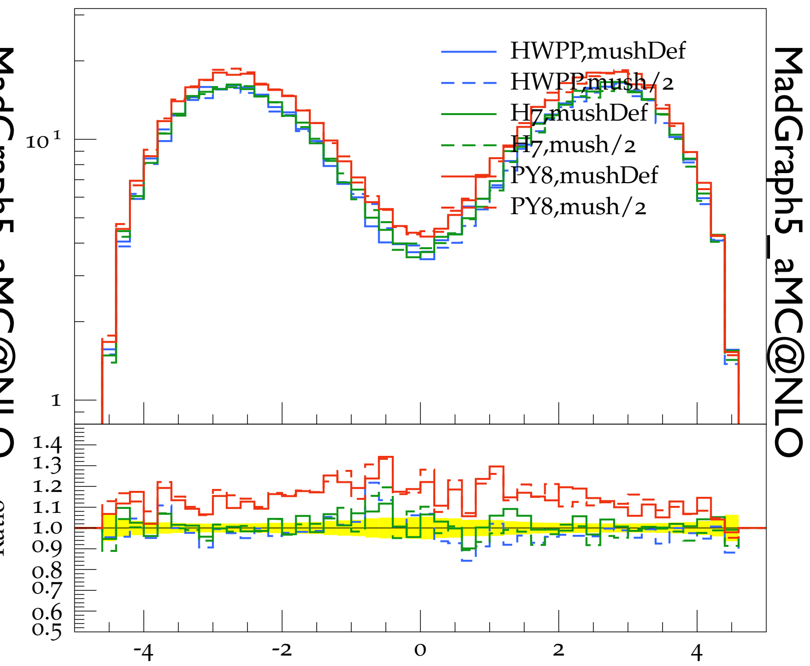


- Same feature observed for similar processes, e.g. Zjj production in VBF or Higgs VBF production

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)

Part 2:
Electro-Weak corrections in VBS

arXiv:1611.02951 & arXiv:1708.00268

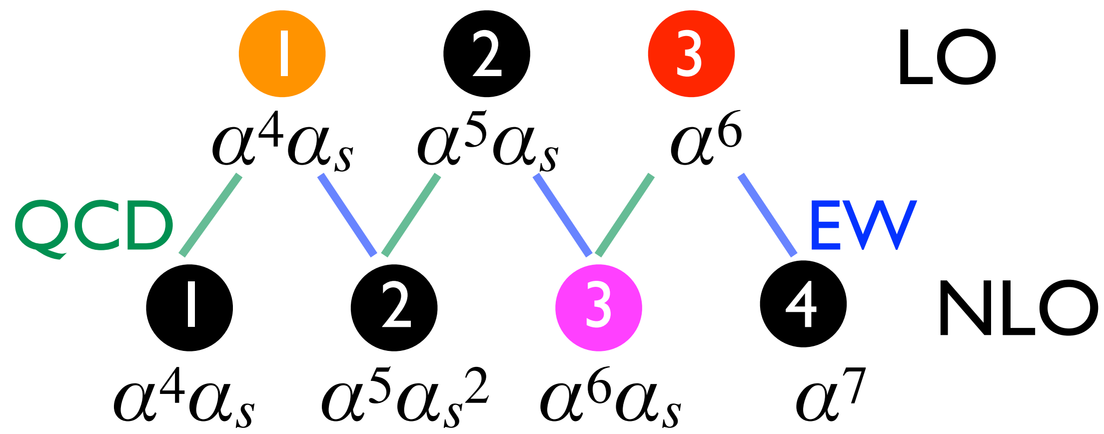
Benedikt Biedermann, Ansgar Denner, Mathieu Pellen,

+ preliminary results from

Ansgar Denner, Stefan Dittmaier, Philipp Maierhofer, Mathieu Pellen, Christopher Schwan

Coupling structure of W^+W^+jj

- W^+W^+jj has three coupling combinations at LO, four at NLO



- In Part 1, we focused on NLO QCD corrections to VBS (order $\alpha^6\alpha_s$). At the same order, also EW corrections on the interference contribute (small in practice).
- When NLO corrections are included, the QCD/interference/VBS separation becomes more blurry
- The hierarchy expected from the coupling constants is violated already at LO. What happens at NLO?
- Modern automated tools (and very smart people) make it possible to compute all NLO contributions together

Complete NLO corrections to W^+W^+ scattering

Biedermann, Denner, Pellen, arXiv:1708.00268

- The complete-NLO corrections for this 2→6 process have been computed with Recola+Collier, including all contributions (non/single/double-resonant diagrams, s/t/u-channel diagrams, …) and employing the complex-mass scheme
  Recola: Actis et al, arXiv:1211.6316 &1605.01090 Collier: Denner et al, arXiv:1407.0087 &1604.6792
- EW corrections to VBS are (much) larger than the QCD ones!
- The coupling hierarchy is violated also at NLO

VBS cuts

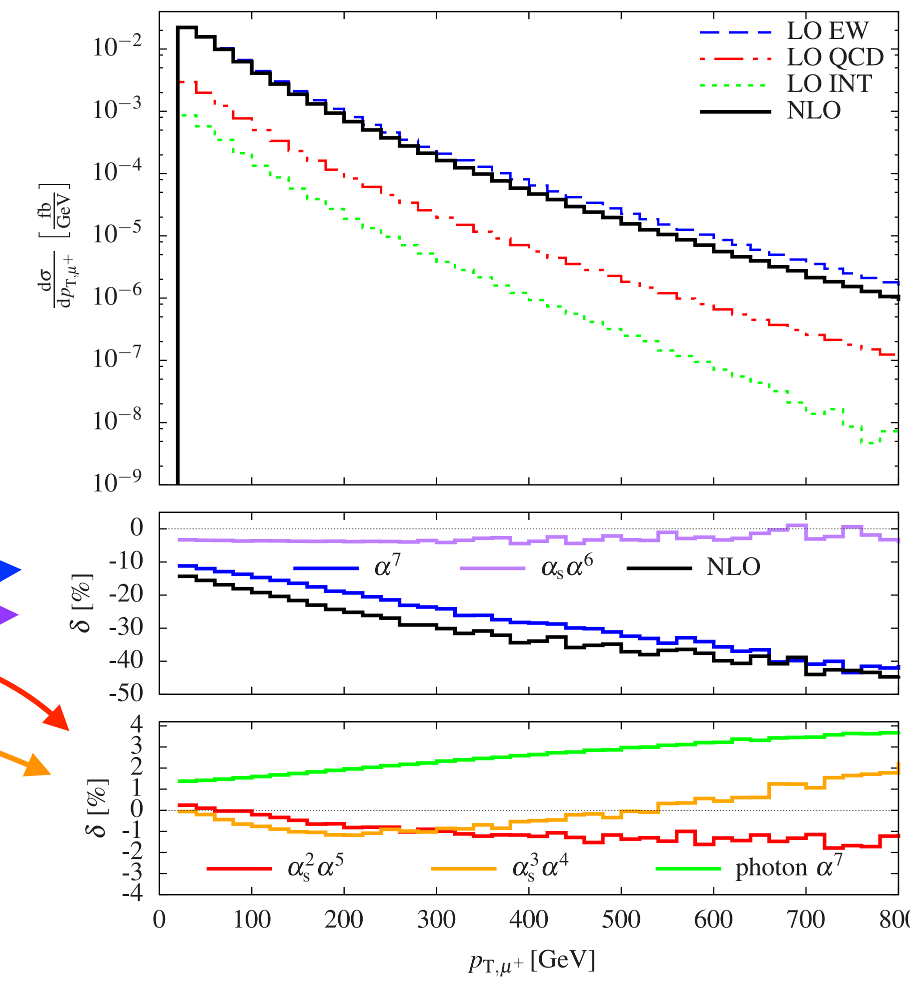
$$p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}, \quad |y_\ell| < 2.5, \quad \Delta R_{\ell\ell} > 0.3.$$
$$E_{\mathrm{T,miss}} = p_{\mathrm{T,miss}} > 40\,\mathrm{GeV}$$
$$p_{\mathrm{T,j}} > 30\,\mathrm{GeV}, \quad |y_\mathrm{j}| < 4.5, \quad \Delta R_{\mathrm{j}\ell} > 0.3,$$
$$m_{\mathrm{jj}} > 500\,\mathrm{GeV}, \quad |\Delta y_{\mathrm{jj}}| > 2.5.$$

VBS (86%) Int. (3%) QCD (11%)

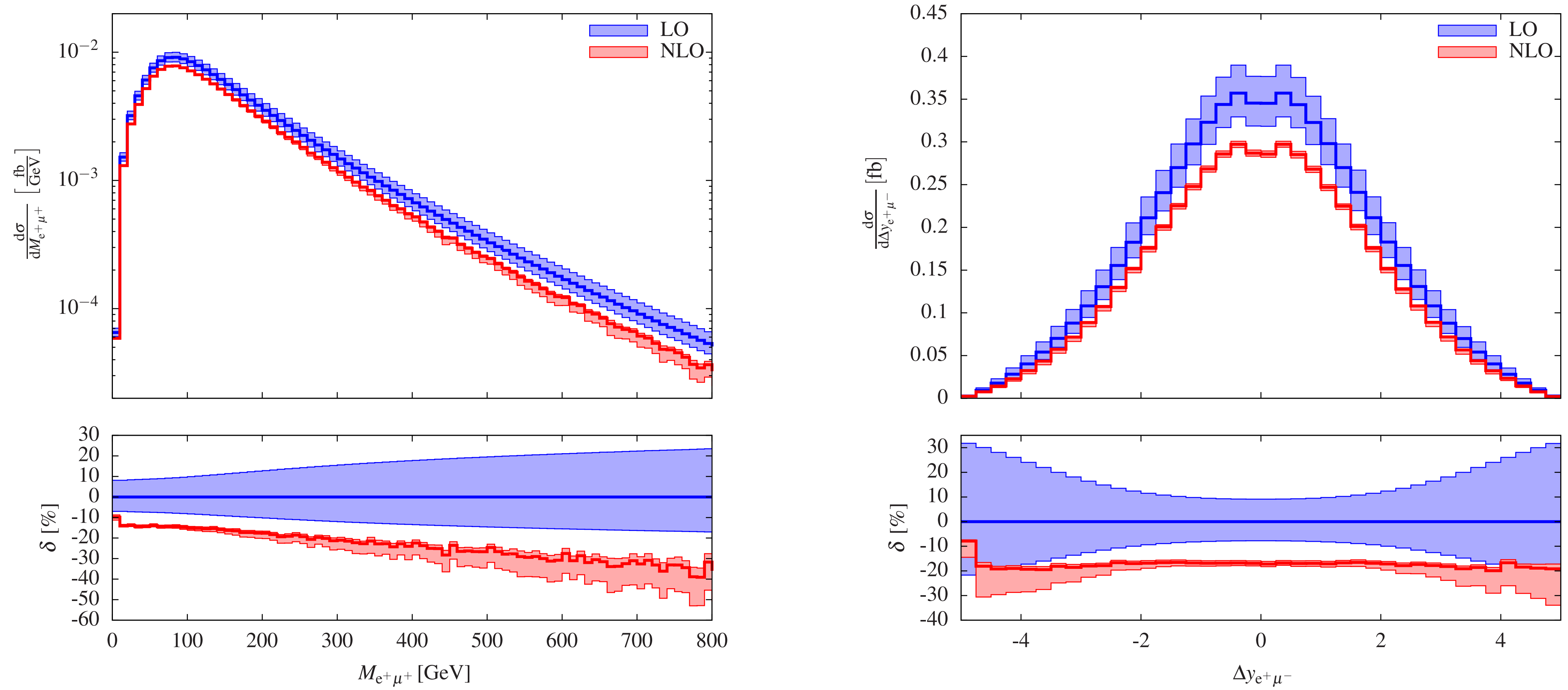
Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	Sum
σ_{LO} [fb]	1.4178(2)	0.04815(2)	0.17229(5)	1.6383(2)

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$
$\delta\sigma_{\mathrm{NLO}}$ [fb]	−0.2169(3)	−0.0568(5)	−0.00032(13)	−0.0063(4)
$\delta\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$ [%]	−13.2	−3.5	0.0	−0.4

VBS, EW corr. VBS, QCD corr.



NLO corrections - W^+W^+ / Combined predictions



[Biedermann, Denner, MP; 1708.00268]

→ Large negative corrections for the full process

→ Corrections dominated by EW correction to EW process

→ Bands do not overlap

M. Pellen, SM@LHC2018

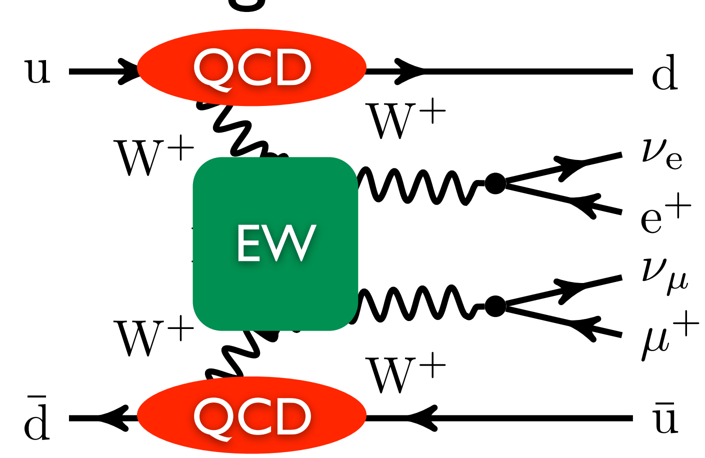
What is happening?

- Already without VBS cuts, VBS is comparable to the QCD background despite the coupling powers. This is due to the larger number of diagrams in VBS Kulesza, Stirling, hep-ph/9912232
- VBS cuts are designed to enhance VBS over QCD background, further reducing also the VBS-QCD interference.
- EW corrections are dominated by corrections in the WW→WW scattering process, which probes large scales (m_{4l}~400 GeV). The bulk of the EW corrections is due to Sudakov logarithms

details can be found in Biedermann et al, arXiv:1611.02951

$$\sigma_{\mathrm{LL}} = \sigma_{\mathrm{LO}} \left[1 - \frac{\alpha}{4\pi} 4 C_{\mathrm{W}}^{\mathrm{ew}} \log^2\left(\frac{Q^2}{M_{\mathrm{W}}^2}\right) + \frac{\alpha}{4\pi} 2 b_{\mathrm{W}}^{\mathrm{ew}} \log\left(\frac{Q^2}{M_{\mathrm{W}}^2}\right) \right]$$

$$C_{\mathrm{W}}^{\mathrm{ew}} = \frac{2}{s_{\mathrm{w}}^2} \qquad b_{\mathrm{W}}^{\mathrm{ew}} = \frac{19}{6 s_{\mathrm{w}}^2}$$



- QCD corrections affect only the quark lines

Are the large EW corrections peculiar to W^+W^+jj?

- Preliminary results show large EW corrections for WZjj too, almost -20% within VBS cuts

Ansgar Denner, Stefan Dittmaier, Philipp Maierhofer,
Mathieu Pellen, Christopher Schwan

Integrated cross section

Integrated xs for pp $\to \mathrm{e}^+\nu_\mathrm{e}\,\mu^+\mu^-\mathrm{jj} + \mathrm{X}$ @ $\sqrt{s} = 13$ TeV for the fiducial PS volume:

LO [fb]	NLO [fb]	$\delta = \frac{\mathcal{O}(\alpha^7)}{\mathcal{O}(\alpha^6)}$ [%]
$0.2362^{+9.433\%}_{-8.022\%}$	$0.1899^{+8.356\%}_{-7.575\%}$	-19.6%

From Christopher Schwan's talk at LoopFest 18

Cuts chosen similar to the ATLAS 8 TeV-analysis [CERN-EP-2016-017]:

- At least two $R = 0.4$ anti-k_t jets with $p_\mathrm{T} > 30$ GeV, $|\eta| < 4.5$, and $\Delta R_{\mathrm{j}\ell} > 0.3$
- $M_{\mathrm{j}_1\mathrm{j}_2} > 500$ GeV, no $\Delta\eta_{\mathrm{j}_1\mathrm{j}_2}$ cut[1]
- $p_{\mathrm{T},\ell} > 20$ GeV and $|y_\ell| < 2.5$
- $p_{\mathrm{T,miss}} > 30$ GeV
- $|M_{\mu\bar{\mu}} - M_Z| < 10$ GeV
- $\Delta R_{\ell\ell} > 0.3$

Other:

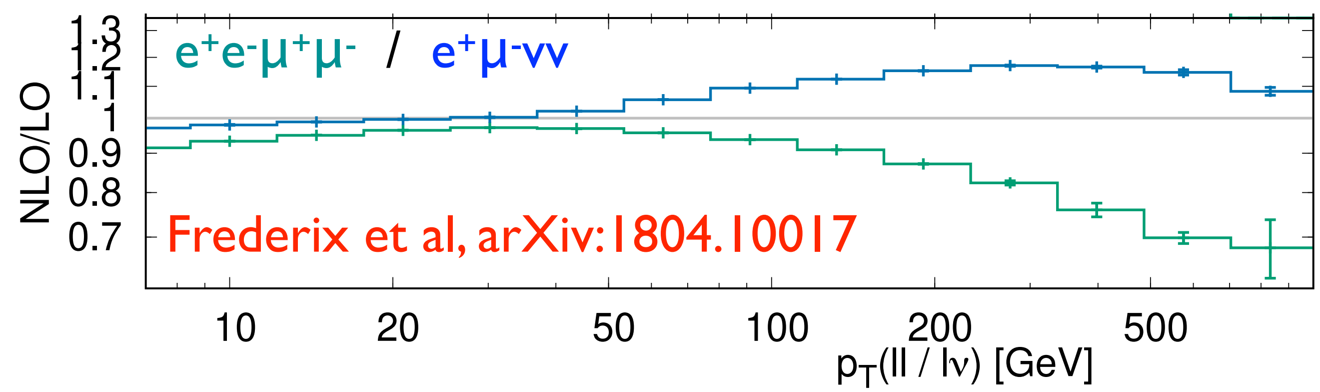
- Photons recombined with charged particles using anti-k_t algorithm with $R = 0.1$
- PDFs: `NNPDF30_nlo_as_0118_qed`
- $\sqrt{s} = 13$ TeV

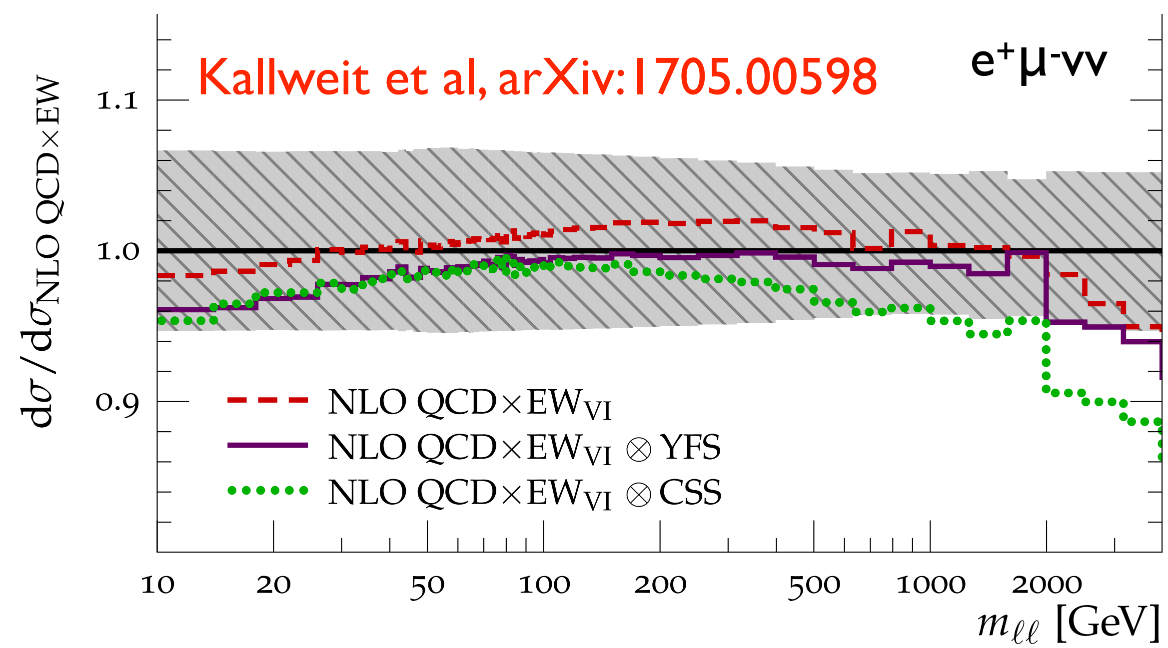
Part 3:
Electro-Weak corrections to multi-(massive)-boson production

Four-lepton production

- EW corrections for 4lep production have been available for some time, for the different production channels (4lep±, 3lep±+met, 2lep± +met)
  Billoni et al, arXiv:1310.1564, Biedermann et al, arXiv:1601.07787, Biedermann et al, arXiv:1605.03419, Biedermann et al, arXiv:1704.05783, Kallweit et al, arXiv:1705.00598, Biedermann et al, arXiv:1708.06938, Frederix et al, arXiv:1804.10017
- Tuned comparison shows good agreement among different codes
  LesHouches 2017, arXiv:1803.07977
- EW corrections amount to few %s (in absolute value). Sign and pattern of EW corrections show different behaviour depending on the process: Sudakov suppression for ZZ / enhancement due to initial γ for WW
- Approximate matching with shower available with Sherpa, valid for photon-inclusive observables

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu$	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}_{\rm EW}$ [fb]
average	448.5414[31]	438.1902[56]
MUNICH+OPENLOOPS	448.5468[45]	438.1920[75]
MOCANLO+RECOLA	448.538[10]	438.193[13]
SHERPA+GOSAM/OPENLOOPS/RECOLA	448.5364[46]	438.186[11]
MADGRAPH5_AMC@NLO	448.541[40]	438.113[70]

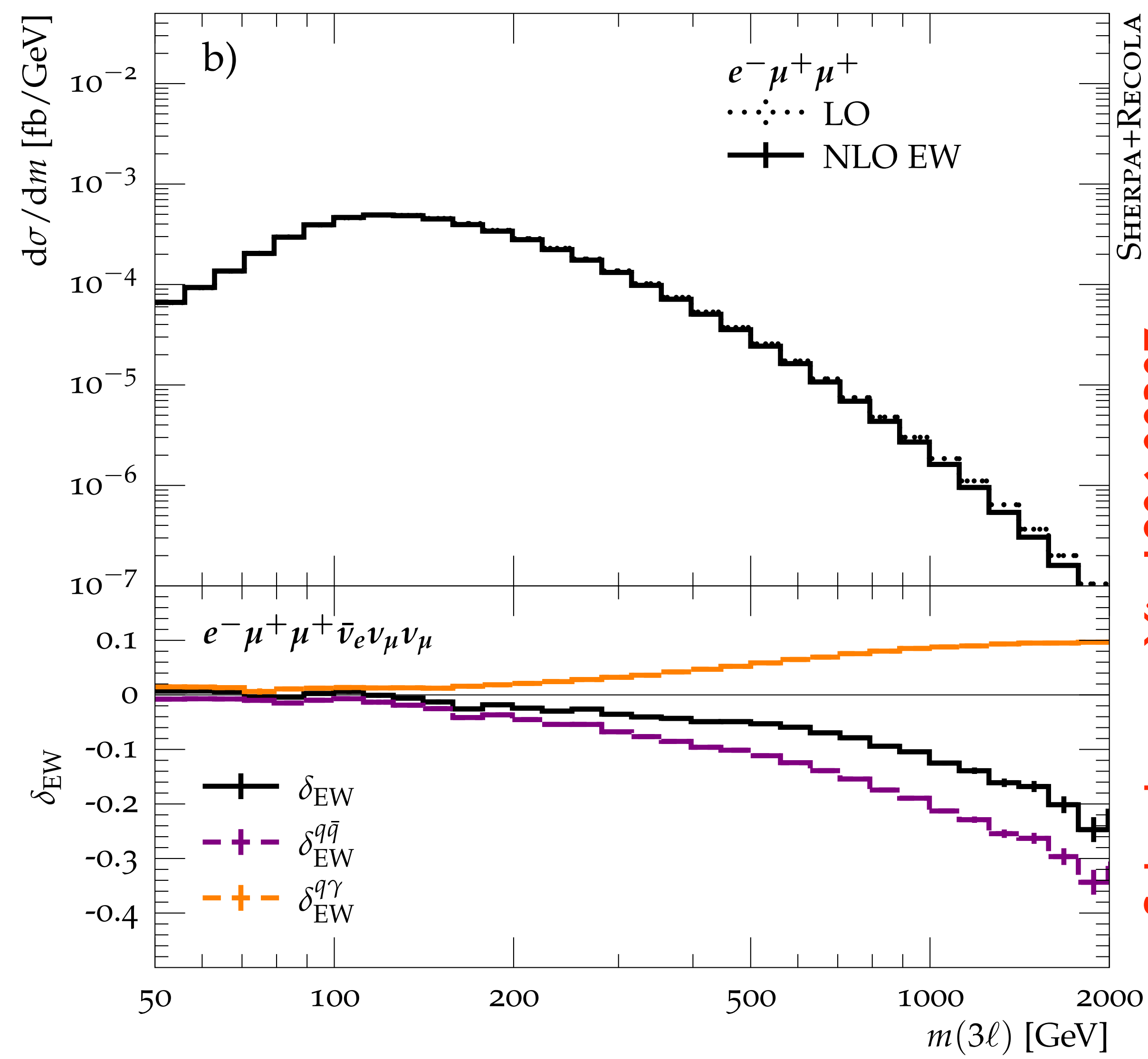




VVV and six-lepton production

- Several results on triple massive-vector boson production are available for stable Vs
  Nhung et al, arXiv:1307.7403, Shen et al, arXiv: 1507.03693, Shen et al, arXiv:1605.00554, Wang et al, arXiv:1610.05876, Dittmaier et al, arXiv:1705.03722, Frederix et al, arXiv:1804.10017
- Recently, results appeared including the vector boson decay (note that VBS includes WWW with VV→lep and V→hadr)
  Schonherr, arXiv:1806.00307
- EW corrections amount up to 10% (in absolute value). Sign and pattern of EW corrections show different behaviour depending on the process (as for VV)
- Partial cancelations between γ-initiaded contributions and Sudakov effects for WWW. Both grow with energy.

$e^+e^+e^-$	δ_{EW}	$\delta_{EW,qq}$	$\delta_{EW,\gamma}$
Incl.	-3.4 %	-7.1 %	3.6 %
M(3l)> 500 GeV	-10.1 %	-18.3 %	8.2 %



Schonherr, arXiv:1806.00307

Conclusions

Part 1:

- 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

Conclusions

Part 2 & 3:

- EW corrections to VBS are large. This seems a common feature of VBS processes (the exact numbers may vary) due to the large scale probed and to the Casimirs of the vector bosons
- For multiple-V productions (VV and VVV), EW corrections are known including the vector-boson decay. Their impact is typically moderate and very process-dependent. Competition between Sudakov suppression and photon-initiated contributions
- EW corrections for VBS have not yet implemented in event generators, they can be included in exp's analyses by reweighting
- Since NLO corrections mix contributions (QCD, VBS, interference) combined measurement of QCD+VBS+interference in the fiducial region should be preferred

VBSCan - COST action

→ EU network lead by Pietro Govoni focused on **VBS**

WG1: Theoretical understanding (Pellen and Zaro)
WG2: Analysis techniques (Manjarres and Mozer)
WG3: Experimental techniques (Duric and Stella Bruni)

→ Money for: short-term travels, meetings, school

- Preliminary website: `https://govoni.web.cern.ch/govoni/VBSCan/`

- Several on-going activities, contact us if you want to join!
  - EFT implementations for VBS
  - VBS polarization
  - … and much more!