Theory developments in VBS simulations

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Standard Model at the LHC 2018
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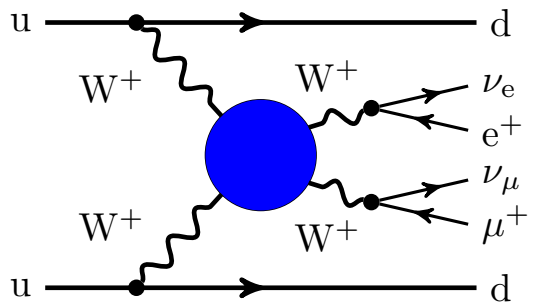
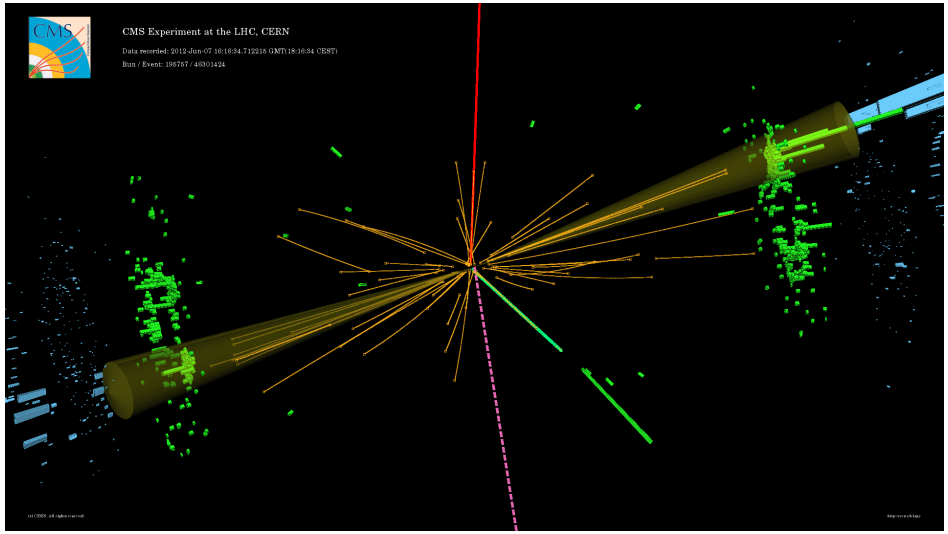
Vector-Boson Scattering (VBS) at the LHC (1)



- Key process to investigate electroweak symmetry breaking
- Crucial role of Higgs boson
- Possibility to measure SM parameters
  → Higgs width: [Campbell, Ellis; 1502.02990]
- Window to new physics
- High multiplicity process
- ...

Vector-Boson Scattering (VBS) at the LHC (2)



- Evidence by ATLAS and CMS at Run-I for $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$

  [1405.6241, 1611.02428, 1410.6315]
- Measurement by CMS at run-II for $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$

  [CMS-PAS-SMP-17-004; 1709.05822]
- Evidence by CMS at Run-II for ZZ [1708.02812]

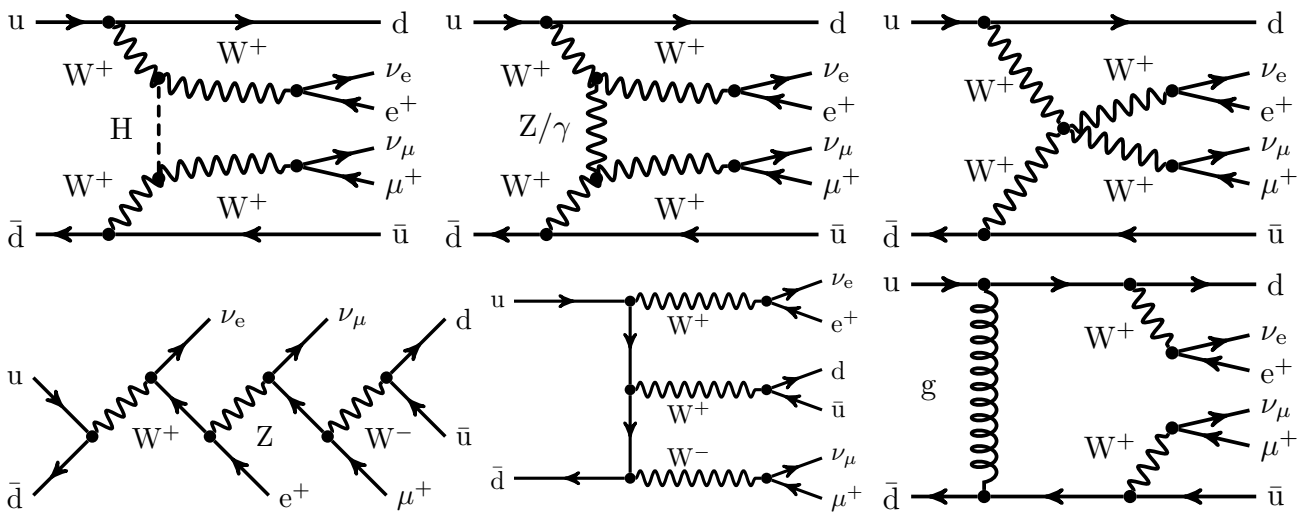
$\rightarrow$ Motivation for this presentation:
Overview of recent theory development for VBS

Example of $pp \to \mu^+\nu_\mu e^+\nu_e jj$

→ All partonic channels to be taken into account:

- $u\bar{u} \to \mu^+\nu_\mu e^+\nu_e d\bar{d}$
- $u\bar{d} \to \mu^+\nu_\mu e^+\nu_e s\bar{c}$
- $uc \to \mu^+\nu_\mu e^+\nu_e sd$
- $\bar{d}\bar{d} \to \mu^+\nu_\mu e^+\nu_e \bar{u}\bar{u}$
- $u\bar{d} \to \mu^+\nu_\mu e^+\nu_e d\bar{u}$
- $u\bar{s} \to \mu^+\nu_\mu e^+\nu_e d\bar{c}$
- $\bar{s}\bar{d} \to \mu^+\nu_\mu e^+\nu_e \bar{u}\bar{c}$

→ Tree amplitudes of order $\mathcal{O}\left(g^6\right)$ and $\mathcal{O}\left({g_s}^2 g^4\right)$

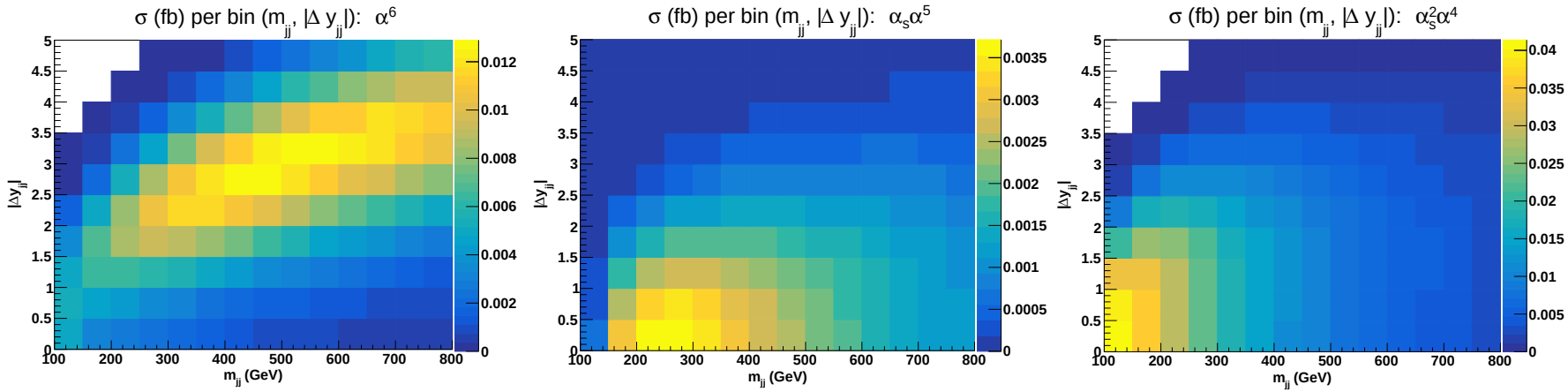


Common feature of all VBS signatures

- LO contributions at: $\mathcal{O}\left(\alpha^6\right)$, $\mathcal{O}\left(\alpha_s\alpha^5\right)$, and $\mathcal{O}\left(\alpha_s{}^2\alpha^4\right)$

$\rightarrow$ EW contribution/signal, interference, and QCD contribution/background

$\rightarrow$ Example of W^+W^+:

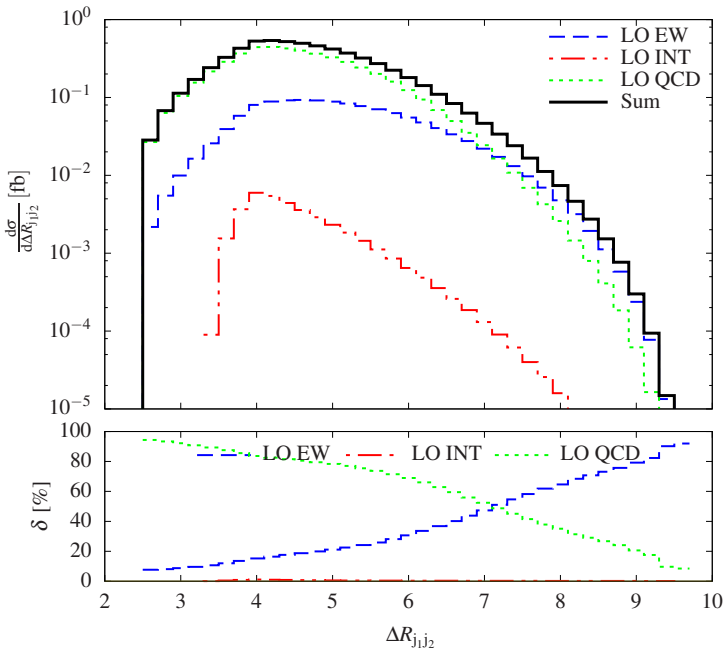


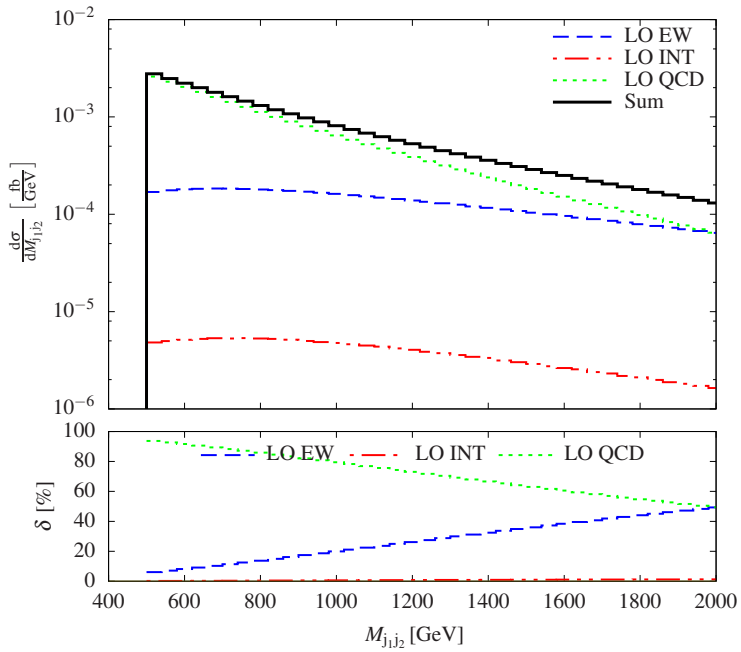
[Ballestrero, MP et al.; 1803.07943]

- The contributions have different kinematic
- Need for exclusive cuts to enhance the EW contribution
  $\rightarrow$ typical cuts are m_{jj} and $|\Delta y_{jj}|$.

Common feature of all VBS signatures

Example of WZ:





[Bräuer, MP et al.; LH proceedings - 1803.07977]

→ Phase-space regions where EW contribution is dominating: very low statistics

→ Challenge for experimental collaborations

→ Need for reliable theoretical predictions:
higher orders, estimate of approximations, parton shower, ...

Outline

- NLO
- Quality of the VBS approximation
- Polarised predictions
- Beyond fixed order
- Final remarks

NLO computations (1)

- $W^{\pm}W^{\pm}$
  - NLO QCD to EW-induced process in VBS approximation

    [Jäger, Oleari, Zeppenfeld; 0907.0580], [Denner, Hošeková, Kallweit; 1209.2389]
  - NLO QCD to QCD-induced process [Melia et al.; 1007.5313, 1104.2327], [Campanario et al.; 1311.6738]
  - Matching to parton shower [Jäger, Zanderighi; 1108.0864], [Melia et al.; 1102.4846]

    $\rightarrow$ Available in VBFNLO or POWHEG-BOX
  - Full NLO QCD and EW to EW- and QCD-induced process

    [Biedermann, Denner, MP; 1611.02951, 1708.00268]
- $W^{\pm}Z$
  - NLO QCD to EW-induced process in VBS approximation

    [Bozzi et al.; hep-ph/0701105]
  - NLO QCD to QCD-induced process [Campanario et al.; 1305.1623]

    $\rightarrow$ Available in VBFNLO

NLO computations (2)

- $\underline{W^+W^-}$
  - NLO QCD to EW-induced process in VBS approximation [Jäger, Oleari, Zeppenfeld; hep-ph/0603177]
  - NLO QCD to QCD-induced process [Melia et al.; 1104.2327], [Greiner et al.; 1202.6004]
  - Matching to parton shower [Jäger, Zanderighi; 1301.1695], [Rauch, Plätzer; 1605.07851]

    $\rightarrow$ Available in VBFNLO or POWHEG-BOX
- $\underline{ZZ}$
  - NLO QCD to EW-induced process in VBS approximation and matching to parton shower [Jäger, Karlberg, Zanderighi; 1312.3252]
  - NLO QCD to QCD-induced process [Campanario et al.; 1405.3972]

    $\rightarrow$ Available in VBFNLO or POWHEG-BOX

NLO computations (3)

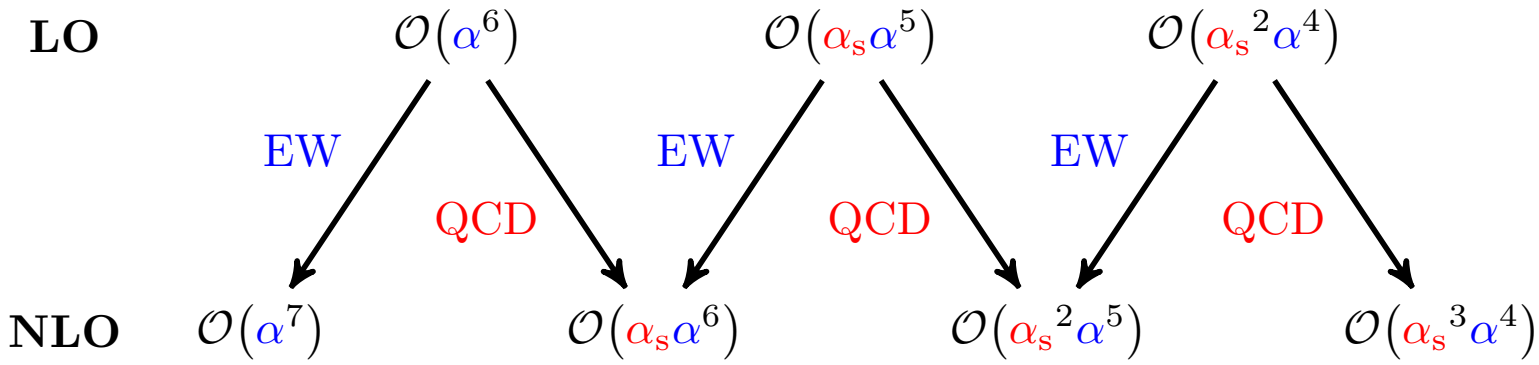
→ All processes known at NLO QCD accuracy matched to PS...
... in VBS approximation
... for both QCD-/EW-induced process

- all available in VBFNLO (apart from QCD-induced W^+W^-)
- partially available in POWHEG-BOX
- possible to generate in MG5_aMC@NLO or SHERPA

→ NLO EW corrections only known for W^+W^+
→ Full NLO computation only known for W^+W^+

NLO corrections

LO contributions at $\mathcal{O}\left(\alpha^6\right)$, $\mathcal{O}\left(\alpha_s\alpha^5\right)$, and $\mathcal{O}\left(\alpha_s{}^2\alpha^4\right)$



NLO contributions at $\mathcal{O}\left(\alpha^7\right)$, $\mathcal{O}\left(\alpha_s\alpha^6\right)$, $\mathcal{O}\left(\alpha_s{}^2\alpha^5\right)$, and $\mathcal{O}\left(\alpha_s{}^3\alpha^4\right)$

$\rightarrow$ Order $\mathcal{O}\left(\alpha_s\alpha^6\right)$ and $\mathcal{O}\left(\alpha_s{}^2\alpha^5\right)$: QCD and EW corrections mix

$\rightarrow$ At NLO: meaningless distinction between EW signal and QCD background

$\rightarrow$ Combined measurement

Common feature to all VBS signatures

NLO corrections - W^+W^+

Calculation of both NLO QCD and EW corrections to
$pp \to \mu^+\nu_\mu e^+\nu_e jj$

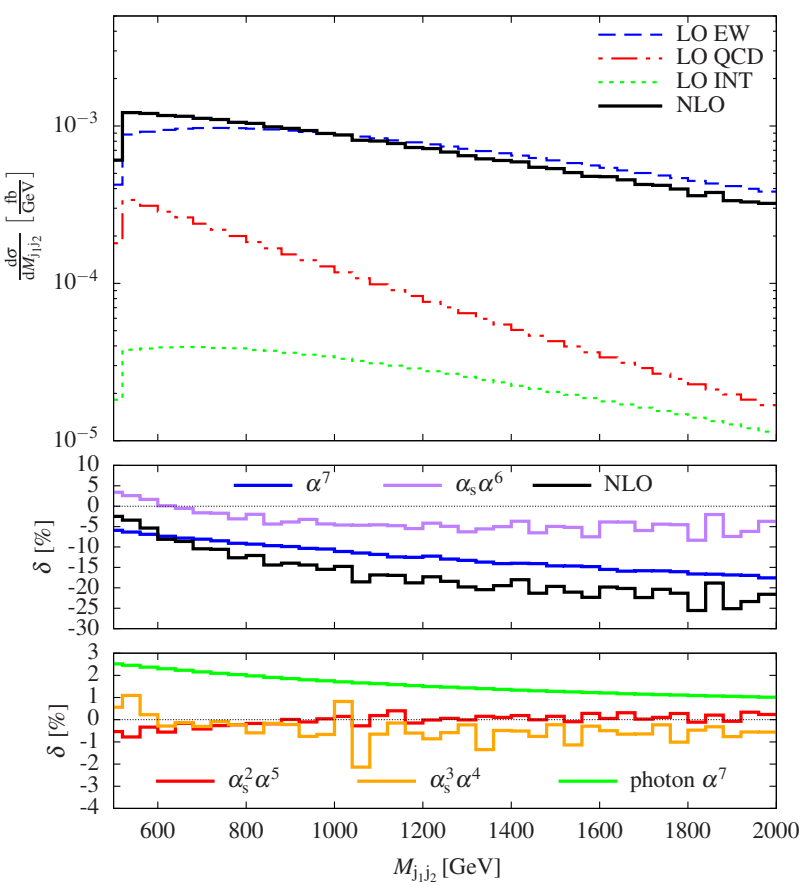
→ NLO fiducial cross sections: (normalised to σ_{LO})

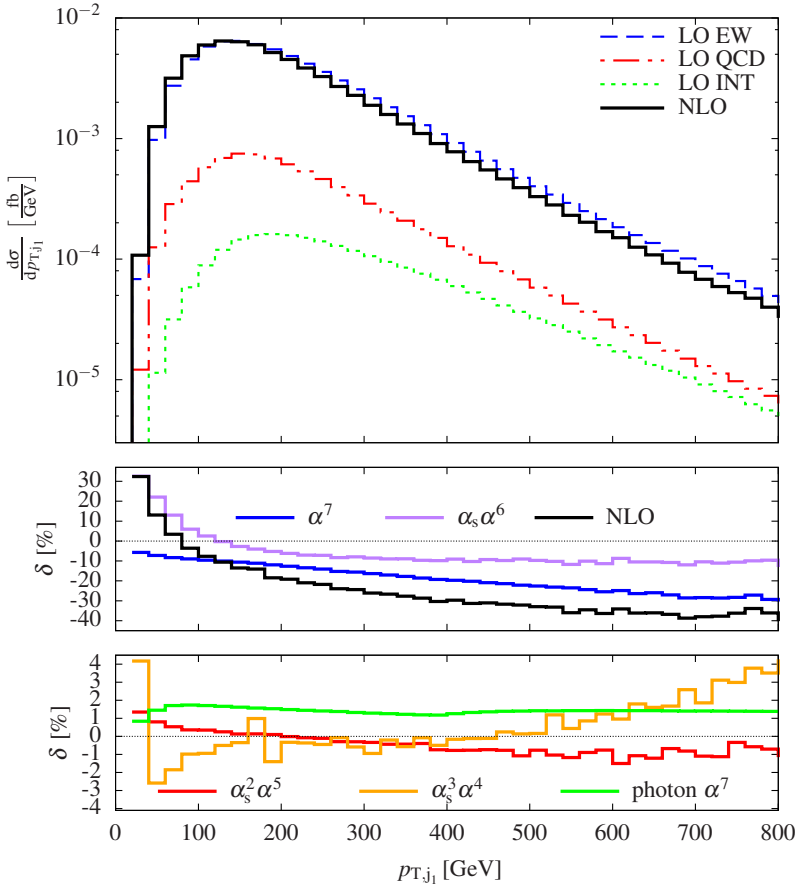
Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{NLO}$ [fb]	$-0.2169(3)$	$-0.0568(5)$	$-0.00032(13)$	$-0.0063(4)$	$-0.2804(7)$
$\delta\sigma_{NLO}/\sigma_{LO}$ [%]	-13.2	-3.5	0.0	-0.4	-17.1

[Biedermann, Denner, MP; 1708.00268]

→ Large EW corrections at $\mathcal{O}(\alpha^7)$
→ Negative corrections at $\mathcal{O}(\alpha_s\alpha^6)$
→ Photon PDF contribution at NLO (not included in NLO definitions):
+1.50% with LUXqed [Manohar et al.; 1607.04266]

NLO corrections - W^+W^+ / Separated contributions



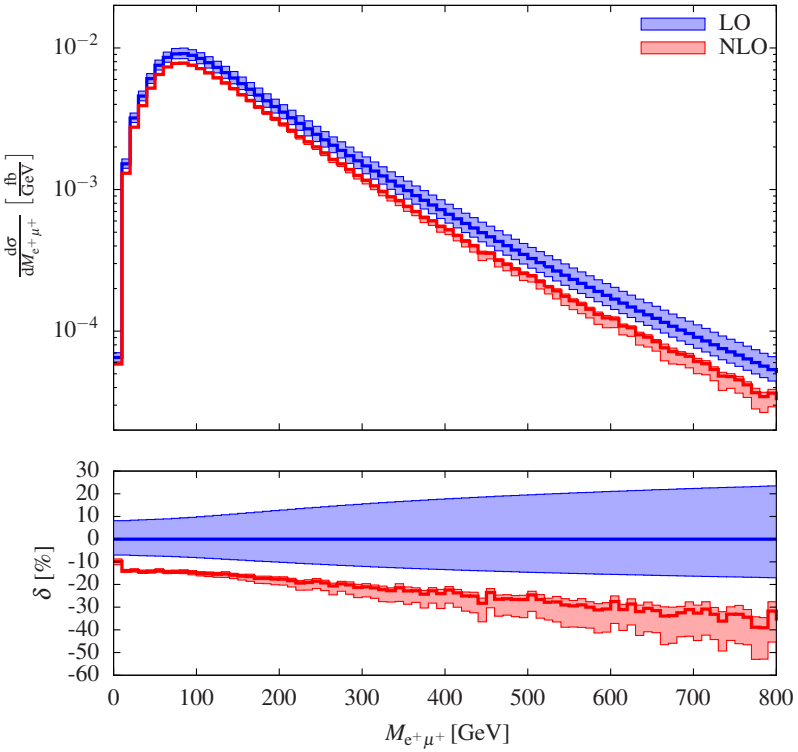


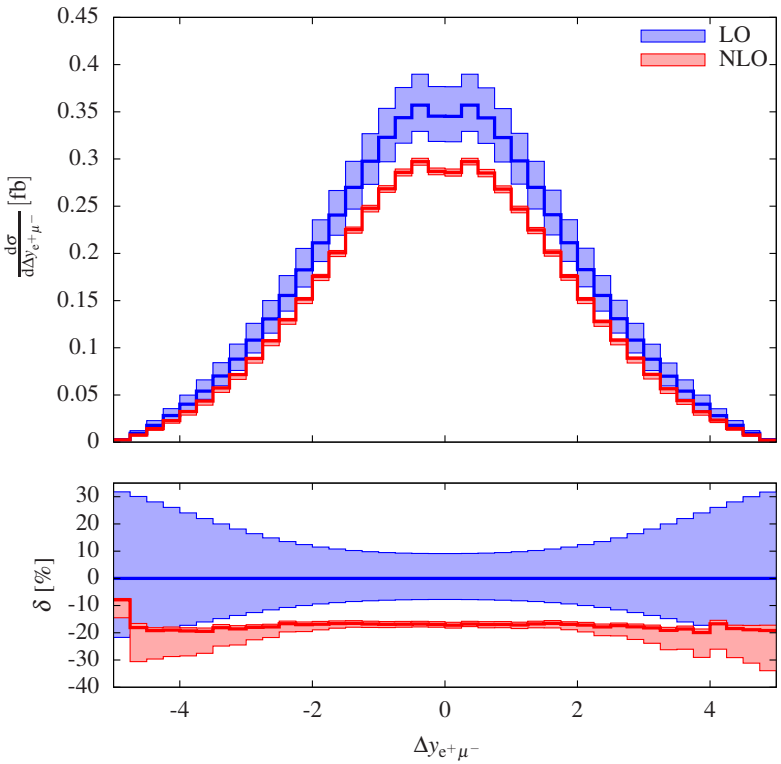
[Biedermann, Denner, MP; 1708.00268]

→ Clear hierarchy of LO contributions

→ Different behaviour of the NLO corrections (normalised to the full LO)

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

NLO corrections

Common feature of all VBS signatures

- EW corrections $\mathcal{O}(\alpha^7)$ large with respect to LO $\mathcal{O}(\alpha^6)$
- Correction of $\mathcal{O}(\alpha_s\alpha^6)$ are expected to be of comparable size
- Small but not negligible photon contribution
- The size of $\mathcal{O}(\alpha_s^3\alpha^4)$ depends strongly on the size of the QCD-induced process at LO

NLO EW corrections

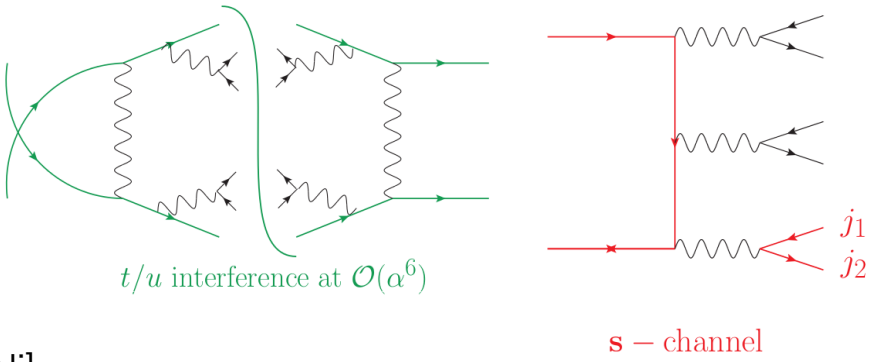
- Electroweak corrections:
  → Leading behaviour: Sudakov logarithms, $\log^2\left(\frac{Q^2}{M_W^2}\right)$
  → Usually in the tail of the distribution (suppressed)
  → Usually small for total cross section
  → Usually smaller than the QCD corrections
- Large corrections not due to VBS cuts
- Using leading logarithm approximation [Denner, Pozzorini; hep-ph/0010201] for $W^+W^+ \to W^+W^+$
  → Good approximation of the full calculation
  → Large corrections explained by the scale of the scattering process and the quantum numbers of the particles involved

  [Biedermann, Denner, MP; 1611.02951]

Large NLO EW corrections:
Intrinsic feature of VBS at the LHC

VBS approximation

→ VBS approximation:
Neglecting s-channel contributions and t/u interferences
Implemented in POWHEG and VBFNLO (including s-channel)



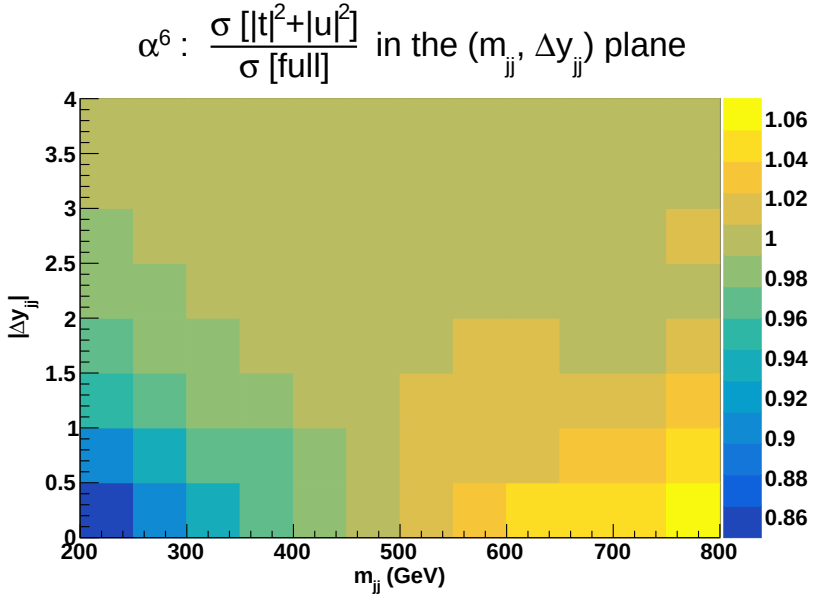
[Source: Pelliccioli]

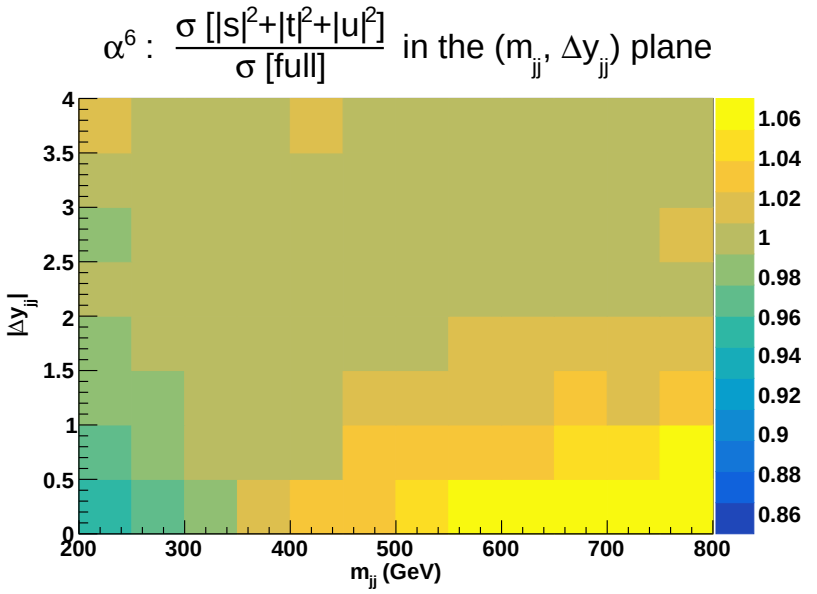
Common feature of all VBS signatures

→ Extension to NLO
Implemented in POWHEG and VBFNLO (including s-channel)

→ Comparison against full computations at NLO
has never been performed before [Ballestrero, MP et al.; 1803.07943]

Quality of the VBS approximation (LO)



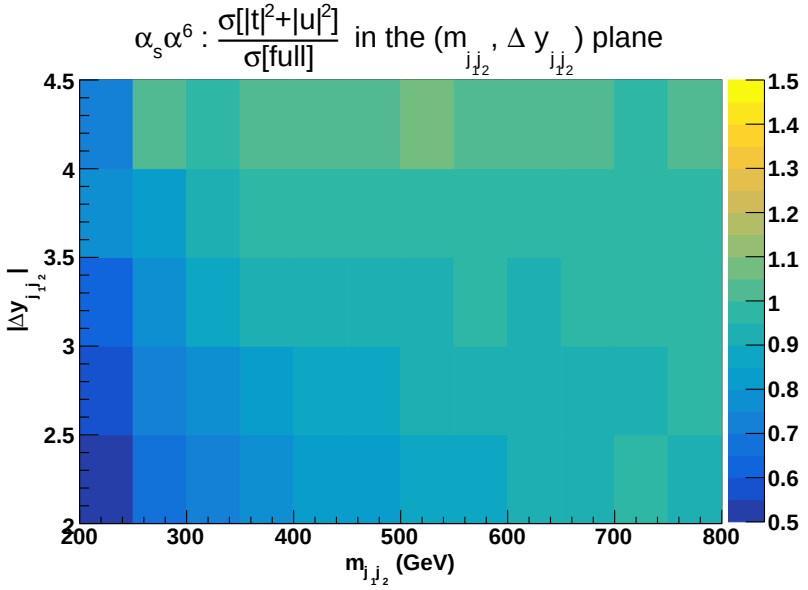


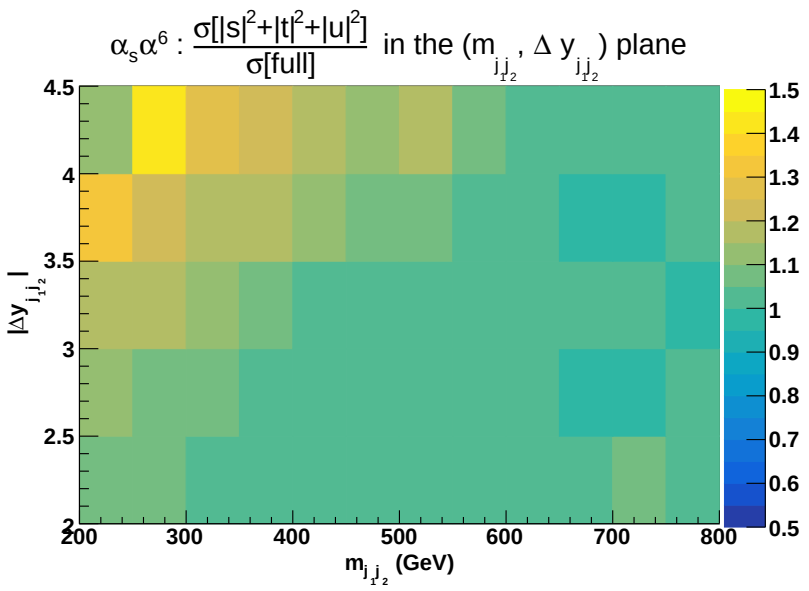
[Ballestrero, MP et al.; 1803.07943]

- For low m_{jj} and low Δy_{jj}, significant s-channel contributions
  → tri-boson contributions with resonant W-boson
- Good approximation in fiducial region for W^+W^+
  → confirmed for $W^\pm Z$ [Bräuer, MP et al.; 1803.07977]

Common feature of all VBS signatures

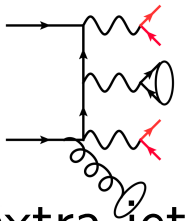
Quality of the VBS approximation (NLO)





[Ballestrero, MP et al.; 1803.07943]

- The approximations are in general worse at NLO
- Importance of *s*-channel at NLO



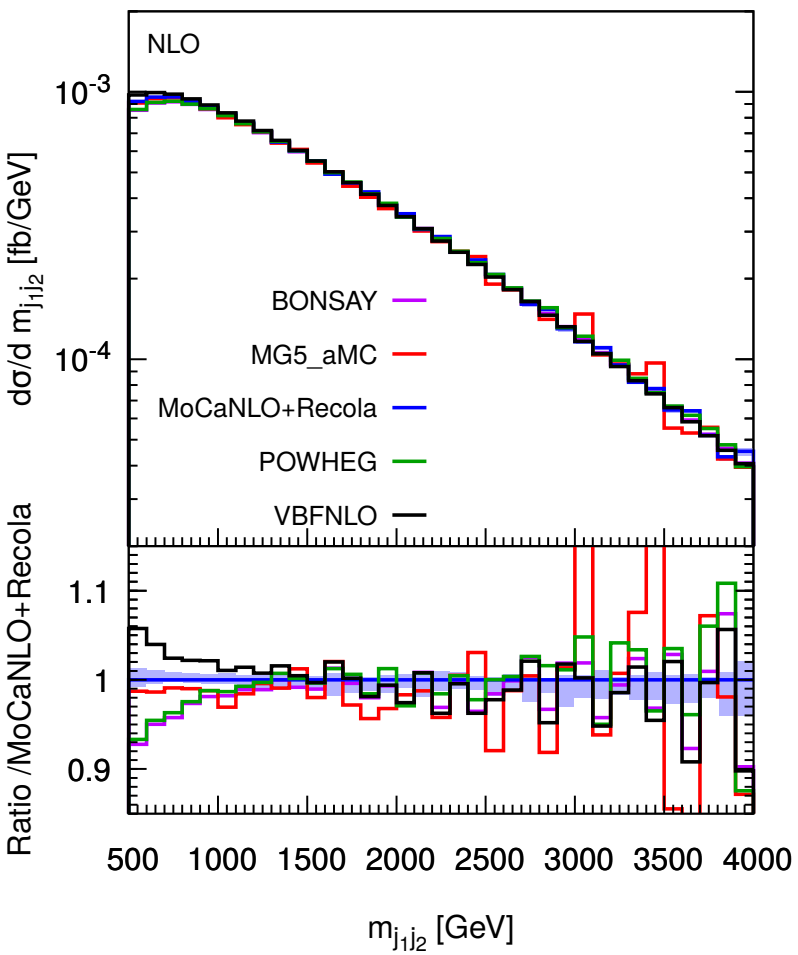
[source: Zaro]

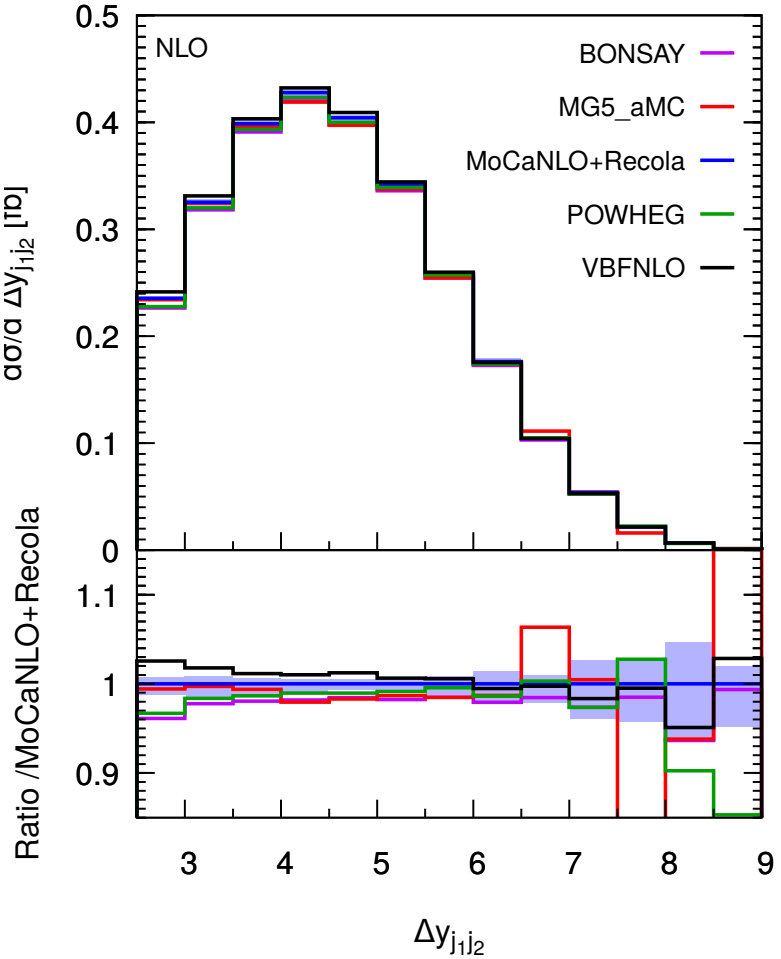
  → Less suppressed at NLO due to extra jet in the real
- Approximation can fail by up to 20% even in fiducial region

  → OK now for current experimental precision ...

  ... but might be important in the future

Quality of the VBS approximation (NLO)





[Ballestrero, MP et al.; 1803.07943]

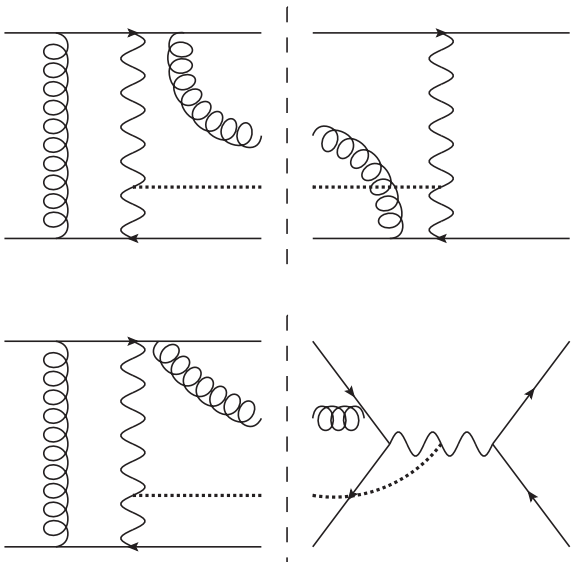
→ Differences lie outside the band

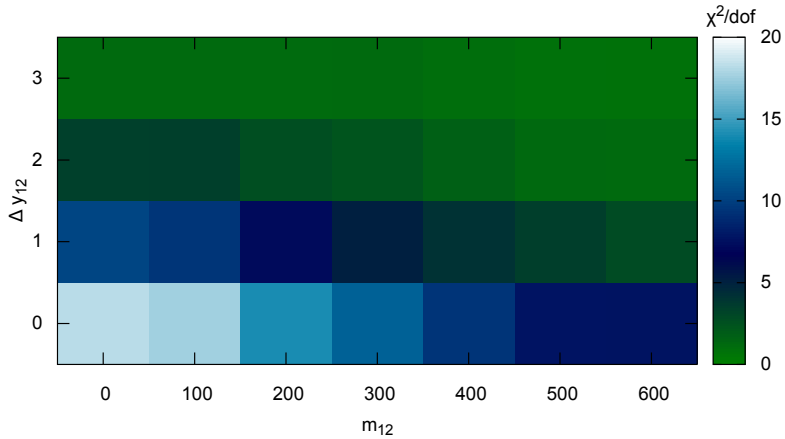
Quality of the VBS approximation

→ Processes with similar colour structure:

- VBF Hjj production
  - → Approximation checked in [Ciccolini, Denner, Dittmaier; 0707.0381, 0710.4749]
  - → Used in NNLO QCD calculations

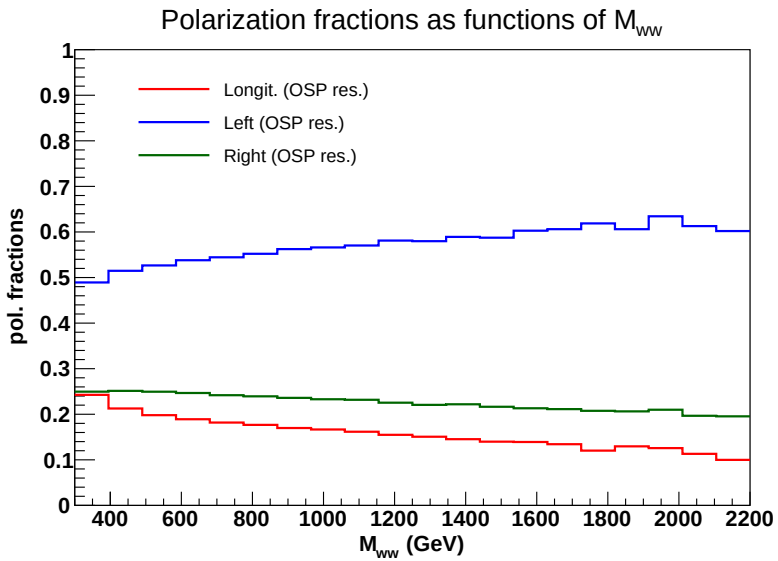
  [Cacciari et al.; 1506.02660], [Cruz-Martinez et al.; 1802.02445]
- VBF Hjjj production
  - → Similar behaviour [Campanario et al.; 1802.09955]

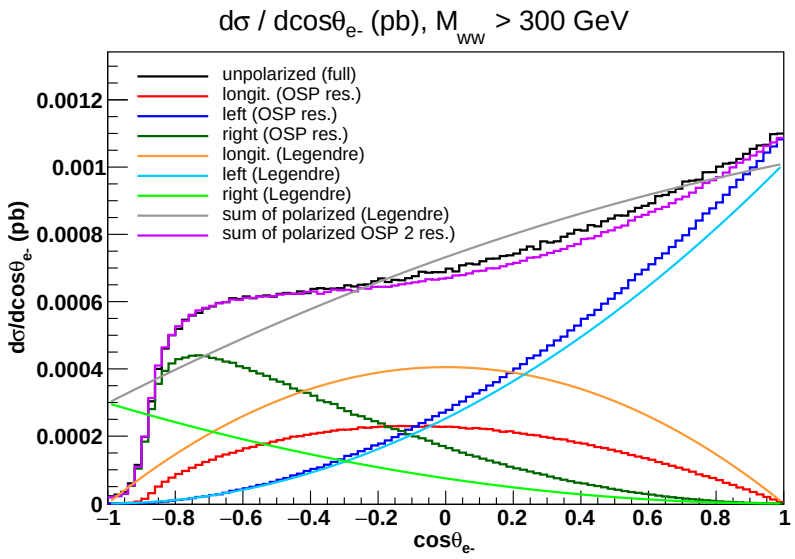




[Campanario et al.; 1802.09955]

Polarised predictions

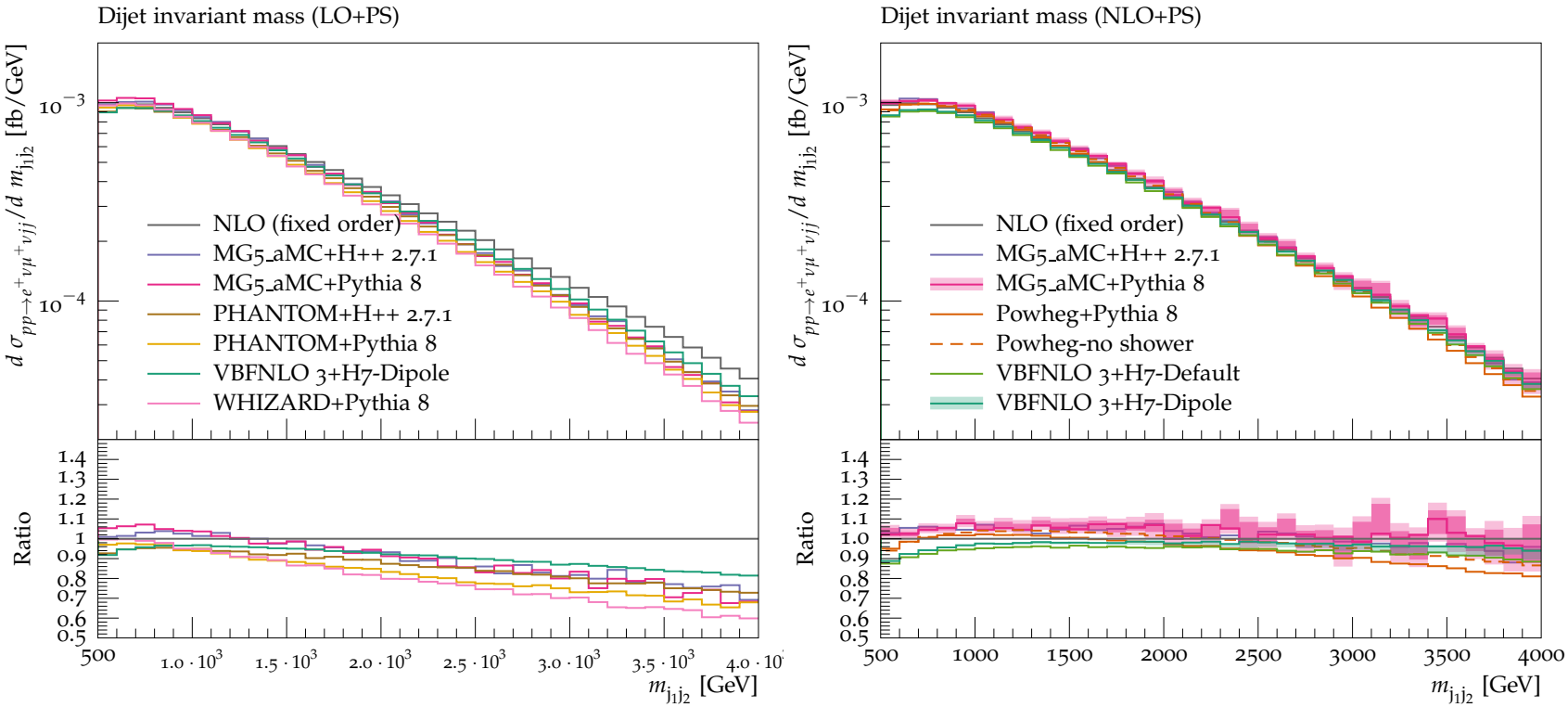




[Ballestrero, Maina, Pelliccioli; 1710.09339]

- Polarisation defined only for on-shell bosons
  → consider only doubly-resonant diagrams
- Example of $\mathrm{W^+W^-}$ [Ballestrero, Maina, Pelliccioli; 1710.09339]
- Method applicable to other signatures
- Method applicable to NLO QCD corrections

Beyond fixed order (1)

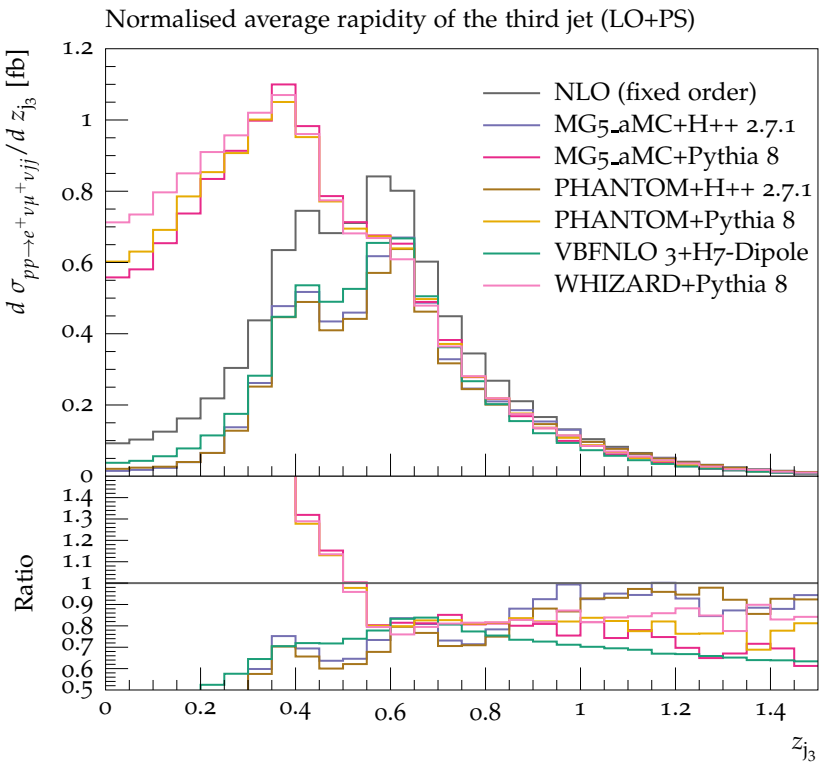


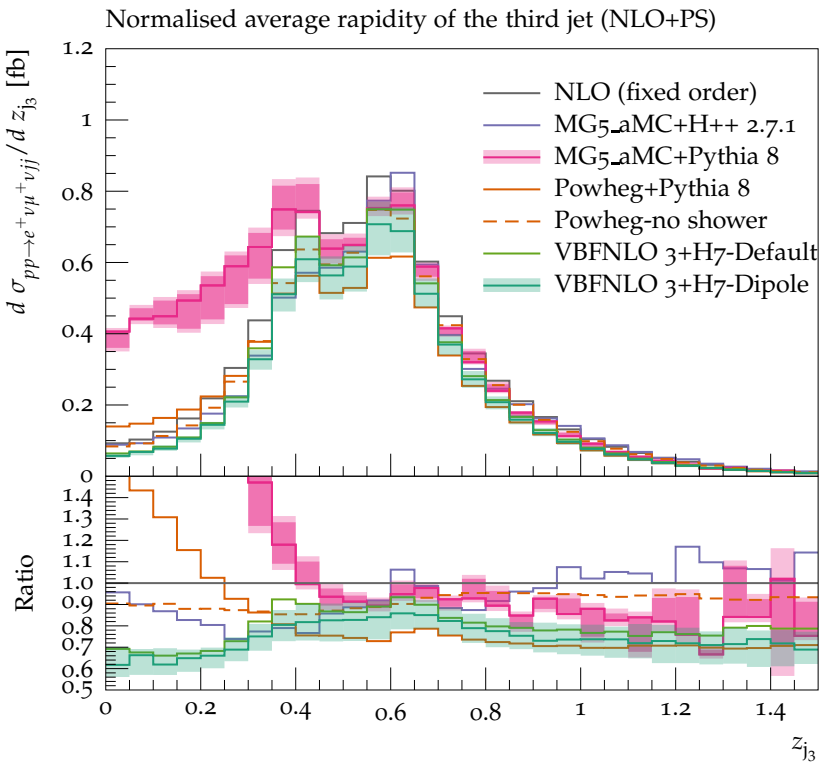
[Ballestrero, MP et al.; 1803.07943]

→ Reasonable agreement at both LO (left) and NLO (right) for observables defined at LO

→ NB: input parameters (masses, widths, PDF, scales) all set to common values

Beyond fixed order (2)





[Ballestrero, MP et al.; 1803.07943]

→ Very large differences for observables related to the third jet (only defined at NLO)

→ Different treatment of recoil in PYTHIA

→ Also observed by CMS in VBF-Z production [CMS; 1712.09814]

→ Also observed for WZ at LO [Bräuer, MP et al.; LH proceedings - 1803.07977]

Summary

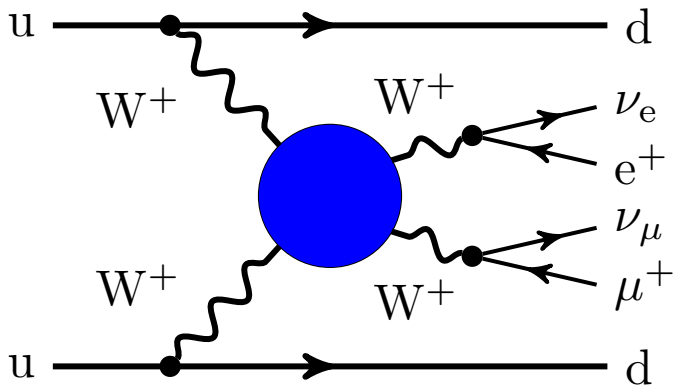
- NLO QCD known for all VBS signature (in VBS approximation) and their irreducible background
- Full NLO corrections only for $\mathrm{W}^+\mathrm{W}^+$ [Biedermann, Denner, MP; 1708.00268]
- NLO EW corrections to VBS [Biedermann, Denner, MP; 1611.02951]
  $\rightarrow$ Intrinsic feature of VBS at the LHC
- VBS approximation [Ballestrero, MP et al.; 1803.07943], [Campanario et al.; 1802.09955]
- Vector-boson polarisation [Ballestrero, Maina, Pelliccioli; 1710.09339]
- Comparison of theoretical predictions

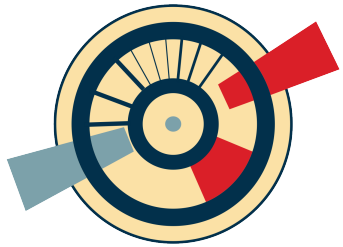
  [Ballestrero, MP et al.; 1803.07943], [Bräuer, MP et al.; LH proceedings - 1803.07977]

  $\rightarrow$ Large differences due to PS

Conclusion

- VBS are challenging processes both theoretically and experimentally
- Significant interest in the theory community
- New territories and lots to be done
- Exciting time ahead of us





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/`
- EWSB Spring school (next week)
  `https://indico.cern.ch/event/673580/`
- Meeting in June in Thessaloniki
  `https://indico.cern.ch/event/706178/`
- Contact us!