WG1 VBF theory report

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Introduction

Outline:

- New Results at NNLO QCD accuracy
- Parton-shower accuracy
- High-pT predictions

NNLO QCD Corrections to VBF-H Production

previous status:

- first calculated in structure-function approach [Bolzoni, Maltoni, Moch, Zaro]
  $\Rightarrow$ inclusive cross section (no cuts on jets)
- in this approach also N^{3}LO QCD calculation available

  Results: [Dreyer, Karlberg]

	$\sigma^{(\text{no cuts})}$ [pb]	$\sigma/\sigma^{\text{NLO}}$
LO	$4.099\,^{+0.051}_{-0.067}$	1.032
NLO	$3.970\,^{+0.025}_{-0.023}$	1
NNLO	$3.932\,^{+0.015}_{-0.010}$	0.990
N3LO	$3.928\,^{+0.005}_{-0.001}$	0.989

small corrections beyond NLO, mostly reduction of scale uncertainties

- much different behaviour when introducing jet and VBF cuts

  [Cacciari, Dreyer, Karlberg, Salam, Zanderighi]

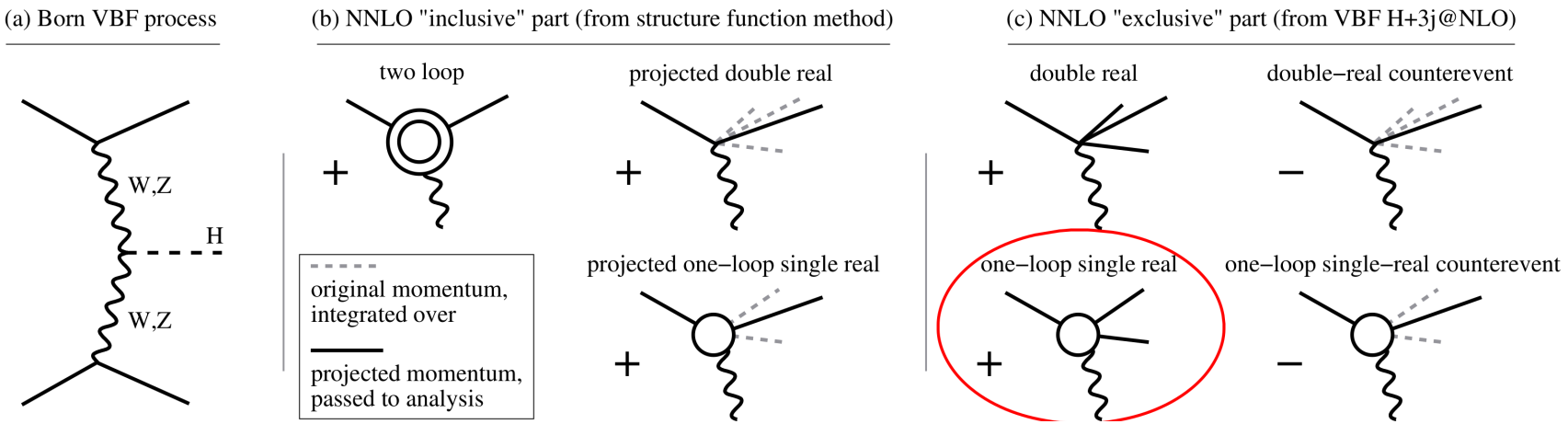
	$\sigma^{(\text{VBF cuts})}$ [pb]	$\sigma/\sigma^{\text{NLO}}$
LO	$0.957\,^{+0.066}_{-0.059}$	1.092
NLO	$0.876\,^{+0.008}_{-0.018}$	1
NNLO	$0.826\,^{+0.013}_{-0.014}$	0.943

OUTDATED

NNLO QCD Corrections to VBF-H Production

recent updates:

- second, independent calculation of differential NNLO QCD effects
  [Cruz-Martinez, Gehrmann, Glover, Huss, arXiv:1802.02445]
- helped discover a bug in the virtuals of the H+3jets calculation
  [Figy, Hankele, Zeppenfeld, arXiv:0710.5621]
- implementation of calculation used in both VBFNLO and POWHEG-BOX
  $\rightarrow$ fixed in version 3.0 β 5 and svn rev. 3470, respectively
- code used in projection-to-Born method of [Cacciari et al., arXiv:1506.02660]
  $\rightarrow$ fixed in public version proVBFH 1.1.0



NNLO QCD Corrections to VBF-H Production

after bugfix:

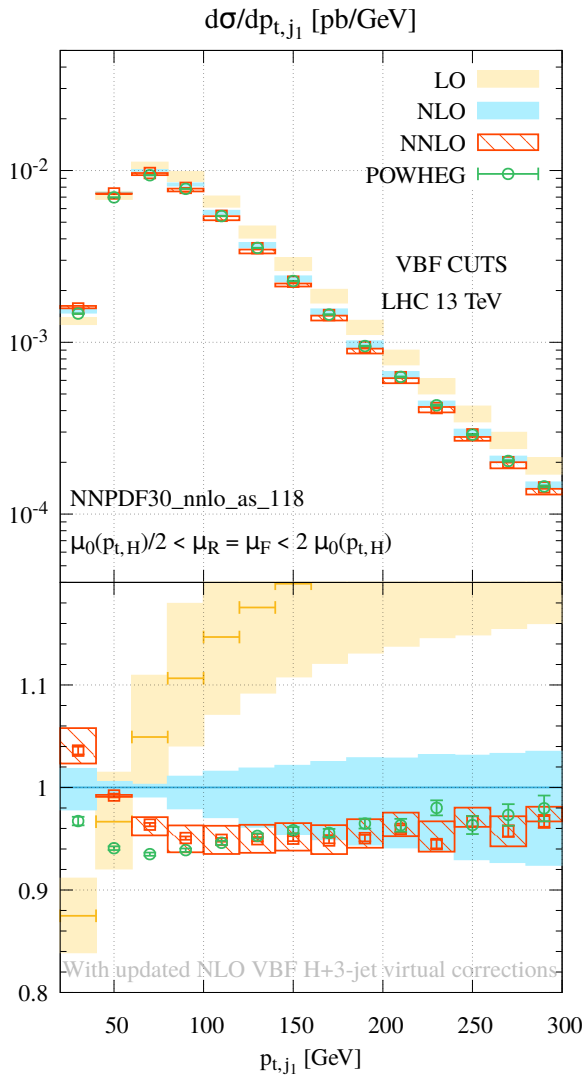
- excellent agreement between both NNLO QCD calculations

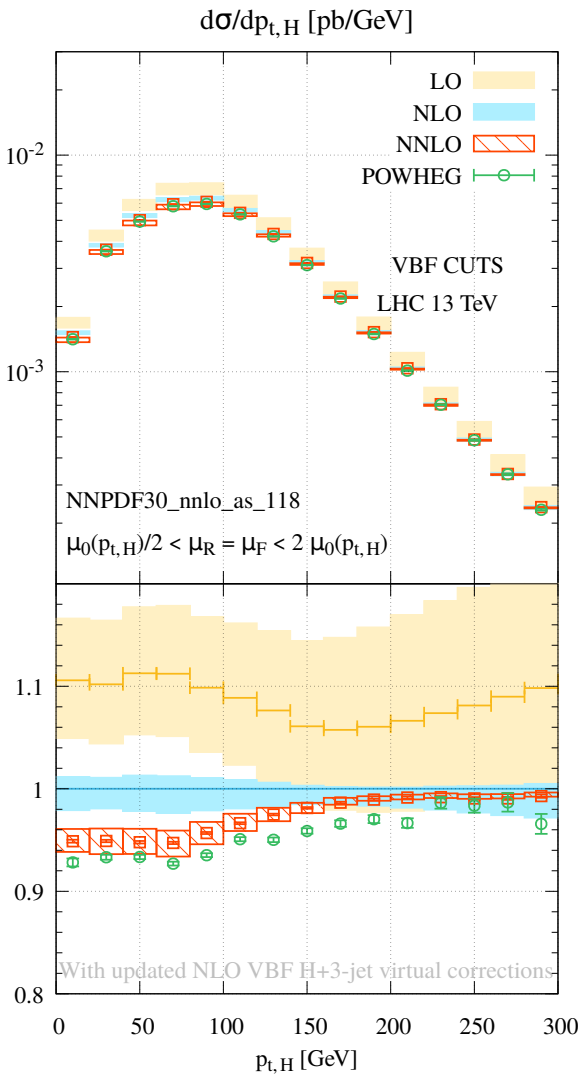
	$\sigma^{\text{(VBF cuts)}}_{1506.02660}$ [pb]	$\sigma^{\text{(VBF cuts)}}_{1802.02445}$ [pb]	$\sigma/\sigma^{\text{NLO}}$
LO	$0.957\,^{+0.066}_{-0.059}$	$0.957\,^{+0.066}_{-0.059}$	1.092
NLO	$0.876\,^{+0.008}_{-0.018}$	$0.877\,^{+0.007}_{-0.017}$	1
NNLO	$0.844\,^{+0.008}_{-0.008}$	$0.844\,^{+0.009}_{-0.009}$	0.962

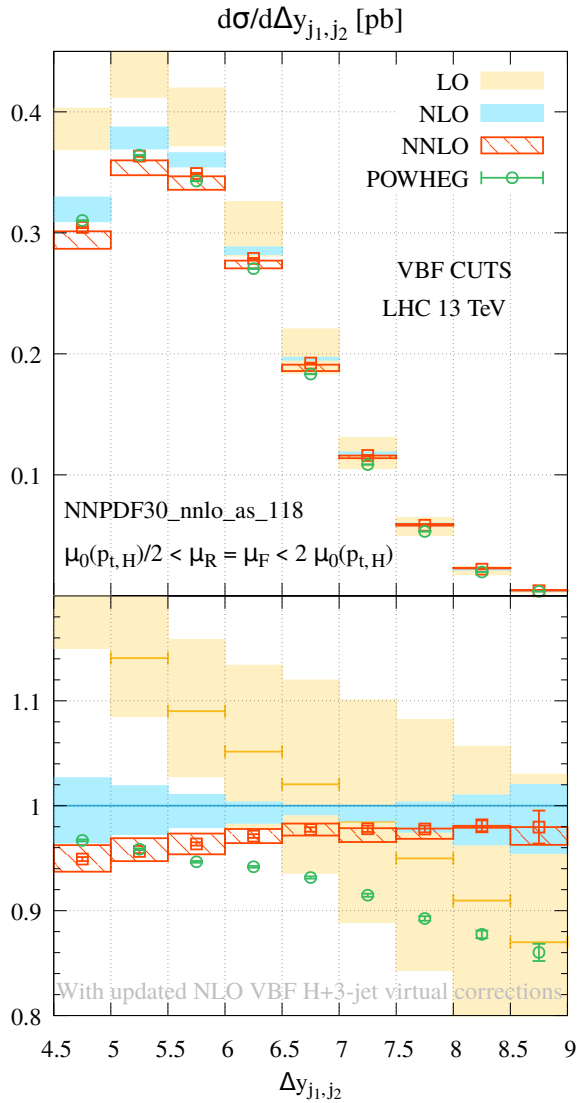
- size of NNLO QCD correction reduced to -3.8%
- scale variation uncertainty stabilised

NNLO QCD Corrections to VBF-H Production

distributions after bugfix:







- reduced scale uncertainty also in distributions
- in general also better agreement with parton-shower prediction

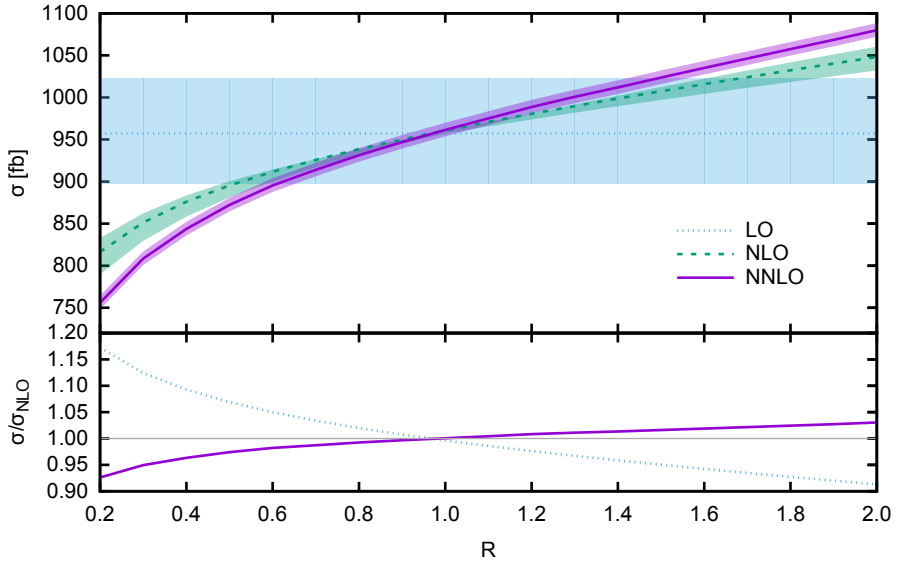
Jet Clustering Dependence

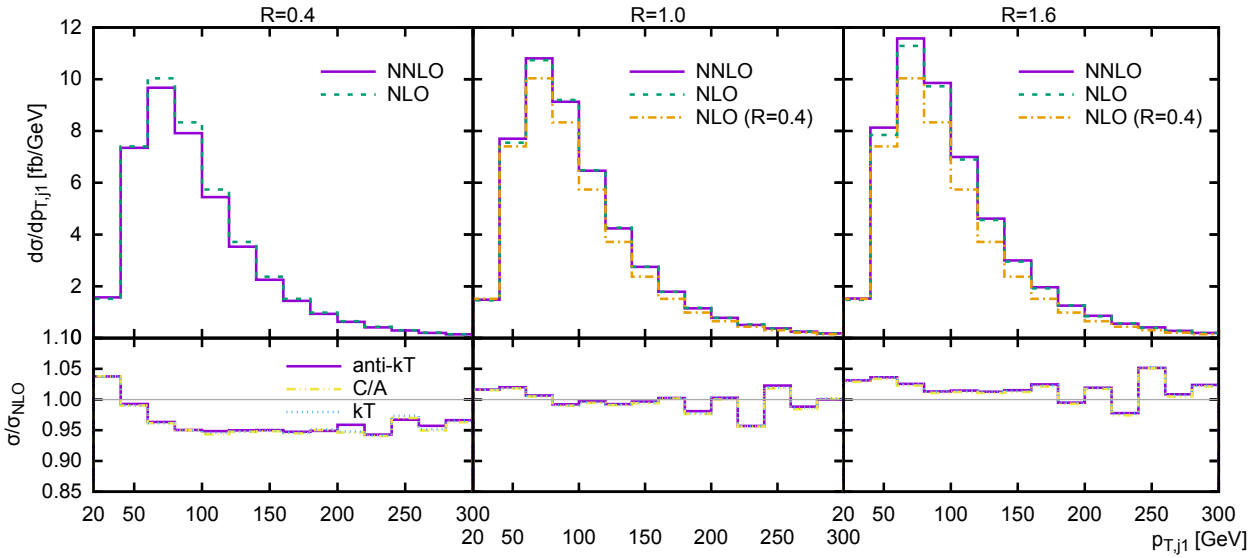
investigation of jet clustering dependence

[MR, Zeppenfeld]

also affected by bugfix

$$\mathrm{d}\sigma^{\mathrm{NNLO}}_{Hjj}(R) = \mathrm{d}\sigma^{\mathrm{NNLO}}_{Hjj}(R{=}0.4) \underbrace{-\mathrm{d}\sigma^{\mathrm{NLO}}_{H3+}(R{=}0.4) + \mathrm{d}\sigma^{\mathrm{NLO}}_{H3+}(R)}_{=\Delta(R)}$$





- matching point stays at $R{=}1.0$
- slope of NNLO line reduced
- some effects at small jet transverse momenta and large jet rapidity difference remain

Parton-Shower Effects

parton-shower and underlying-event systematics
play an important role in VBF selections

⇒ study

Preliminary

[Jäger, Karlberg, MR, Zaro]

compare predictions at NLO+PS accuracy
from

- MG5_aMC
- Powheg-Box
- VBFNLO 3

⊗

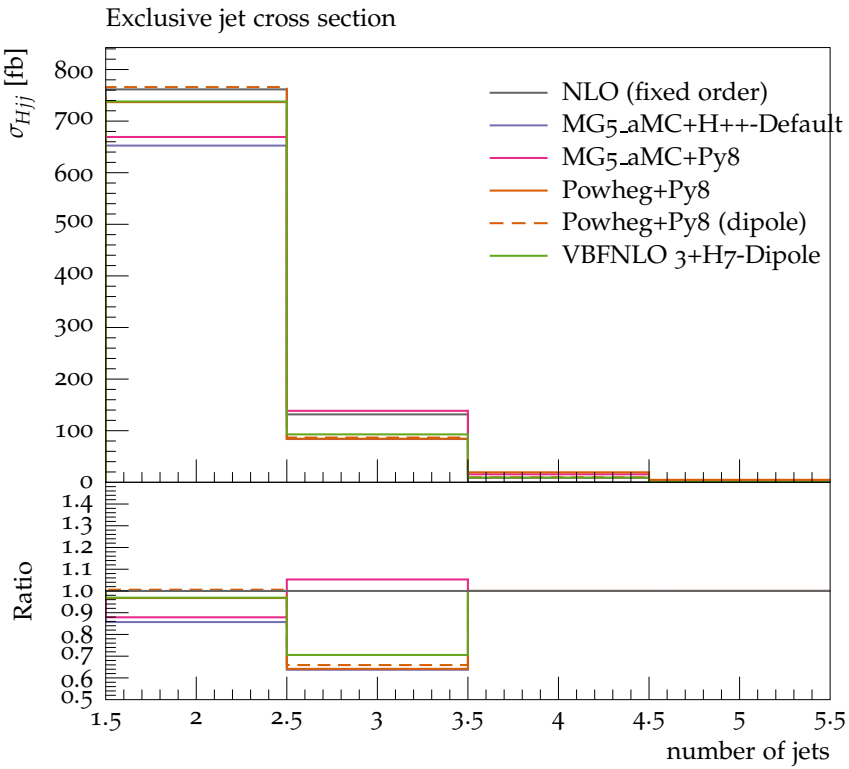
- Pythia 8
- Herwig 7

vs fixed-order NNLO QCD

(results shown:
vs fixed-order NLO QCD,
MG5_aMC + H++2.7.1-Default)

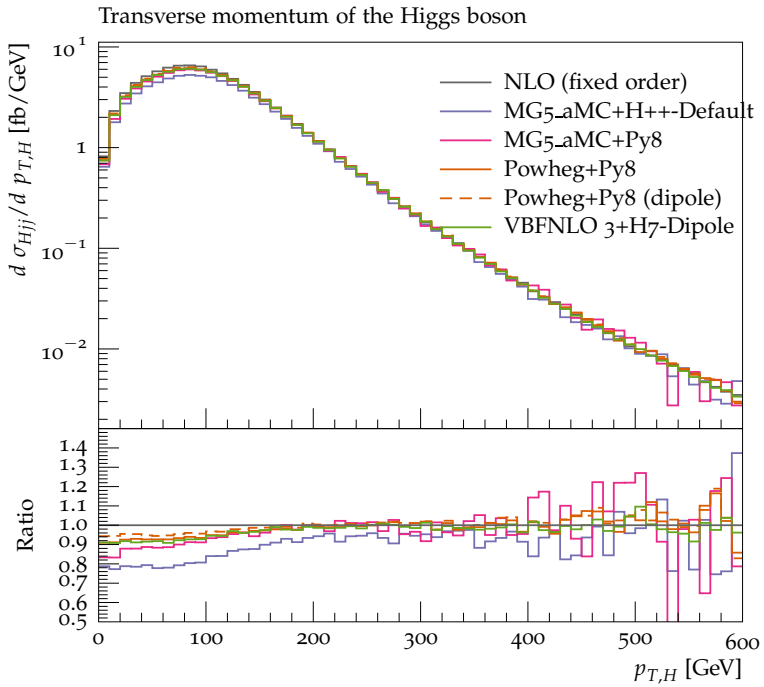
current level of comparison:

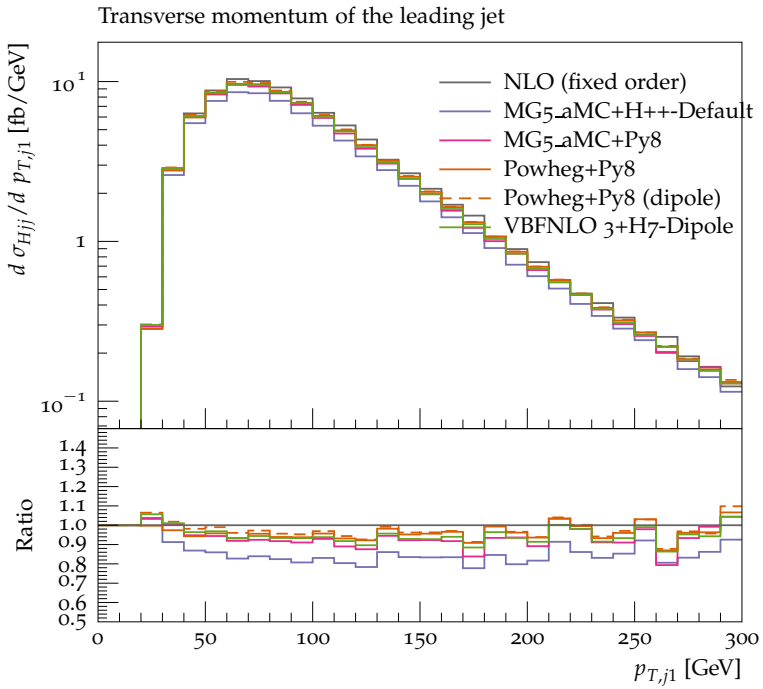
- ✓ parton shower
- ✓ hadronization
- X hadronic decays
- X multi-parton interactions



Parton-Shower Effects

observables present at LO





- in general good agreement within different parton-shower predictions
  $\leftrightarrow$ investigate MG5_aMC+H++-Default deviation after update to H7-Default
- cross section reduction compared to fixed-order NLO
  $\rightarrow$ effect of additional radiation
  $\rightarrow$ out-of-jet-cone emissions reduce energy of jets
  $\leftrightarrow$ invariant-mass cut on tagging jets
  $\rightarrow$ well understood

Central-Jet Veto

- jet activity between the two tagging jets strongly suppressed in VBF

  $\leftrightarrow$ not the case in QCD-induced "gluon-fusion" *Hjj* production

- veto on additional central jets can help to significantly reduce QCD-induced background without losing much of the signal [Barger, Phillips, Zeppenfeld '94]

- when adding parton-shower effects:

  significantly different central jet activity predicted by various codes

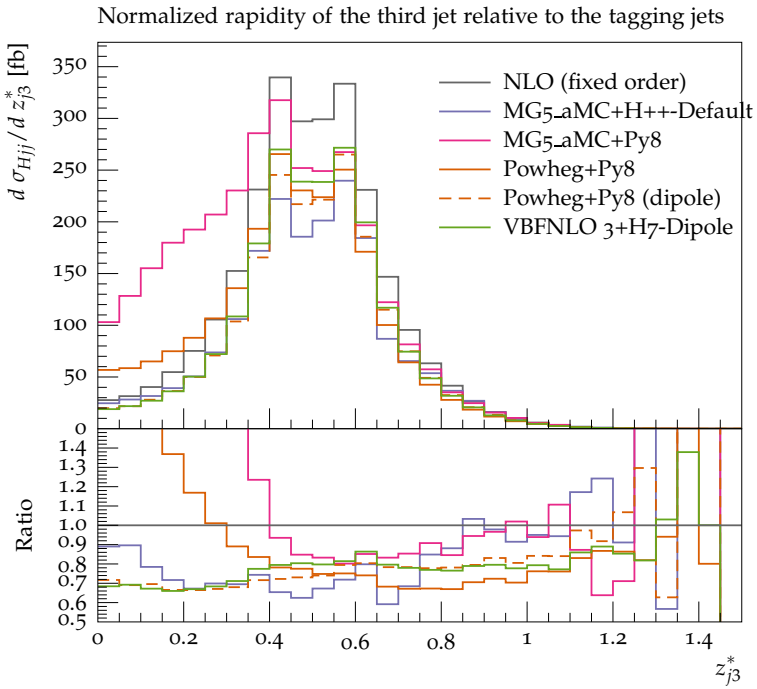
  disagreement on distribution of number of jets [Nason, Oleari]

- third-jet distributions stabilise when VBF-H+3jets NLO QCD matched to parton shower [Jäger, Schissler, Zeppenfeld]

- differences in modelling shift to higher jet multiplicity

Parton-Shower Effects

observables related to the third jet



Definition:

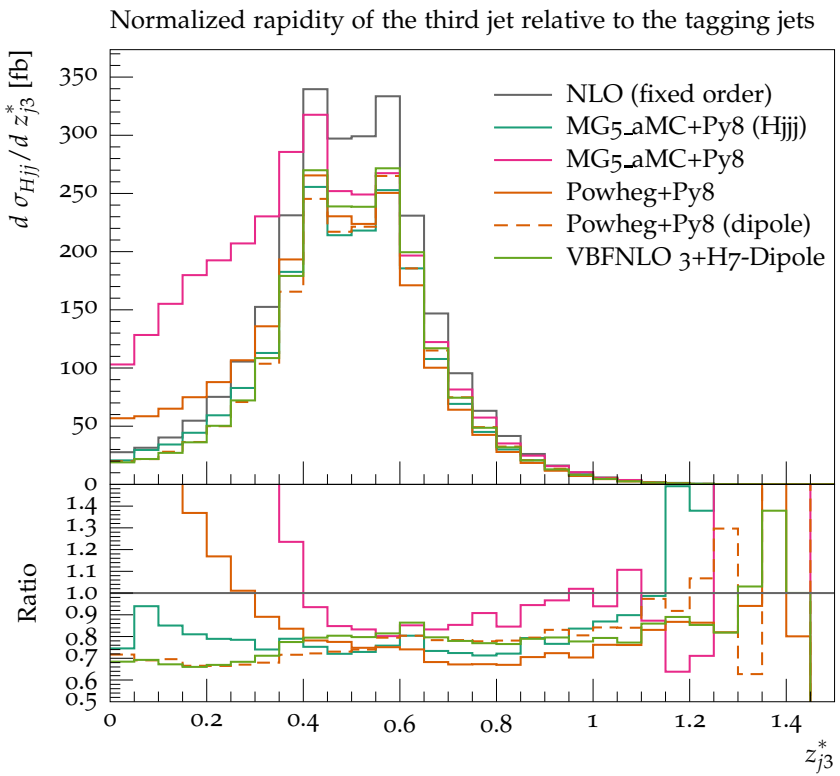
$$z^*_{j3} = \frac{\left| y_{j3} - \frac{y_{j1}+y_{j2}}{2} \right|}{\left| y_{j1} - y_{j2} \right|}$$

$\rightarrow$ position of tagging jets at $z^*_{j3} = 0.5$

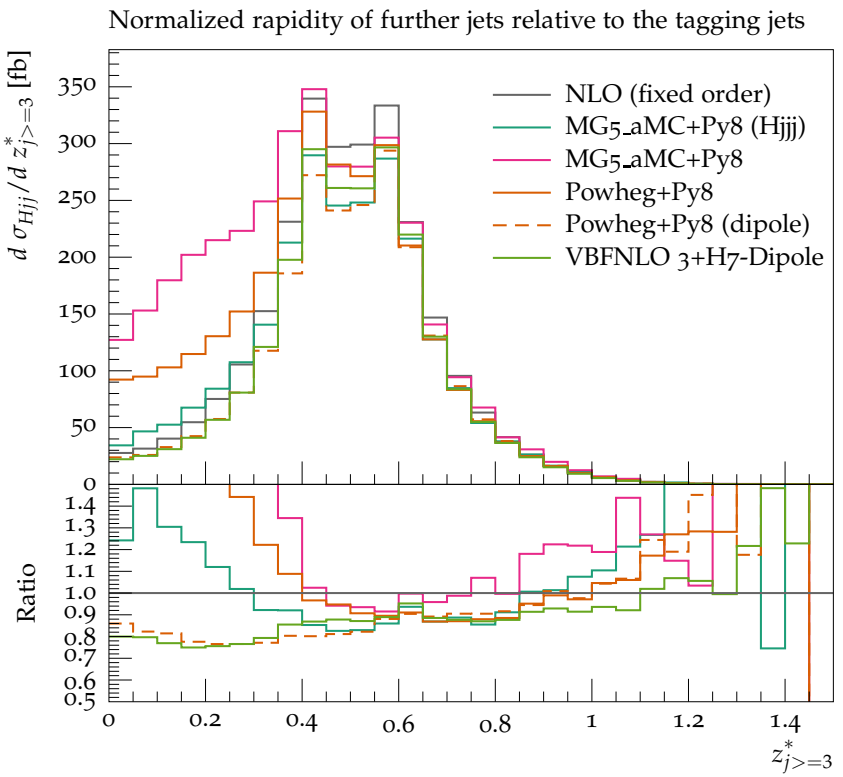
- fixed order: Hjjj LO precision
- widely different predictions in central region ($z^*_{j3} < 0.5$)
- Herwig 7 (both dipole and angular-ordered PS): reduction of jet activity compared to fixed-order prediction
- Pythia 8:
  large enhancement
  owing to modelling as initial-initial / final-final recoils with huge available phase space
- Pythia 8 (dipole):
  option `SpaceShower:dipoleRecoil = on`
  more dipole-style treatment of initial-final dipoles
  $\rightarrow$ suppression
  $\leftrightarrow$ not compatible with MC@NLO matching of MG5_aMC (intricate changes in MC counter terms required)
- same effect seen in VBS-W^+W^+jj recently
  [Ballestrero et al. (VBSCAN), arXiv:1803.07943]

Parton-Shower Effects

third jet



third and further jets



- fixed order: Hjjj LO precision
- reduction in central jet activity also predicted when matching H+3jets NLO from MG5_aMC to Pythia 8
- enhancement effects again when including further jets as well

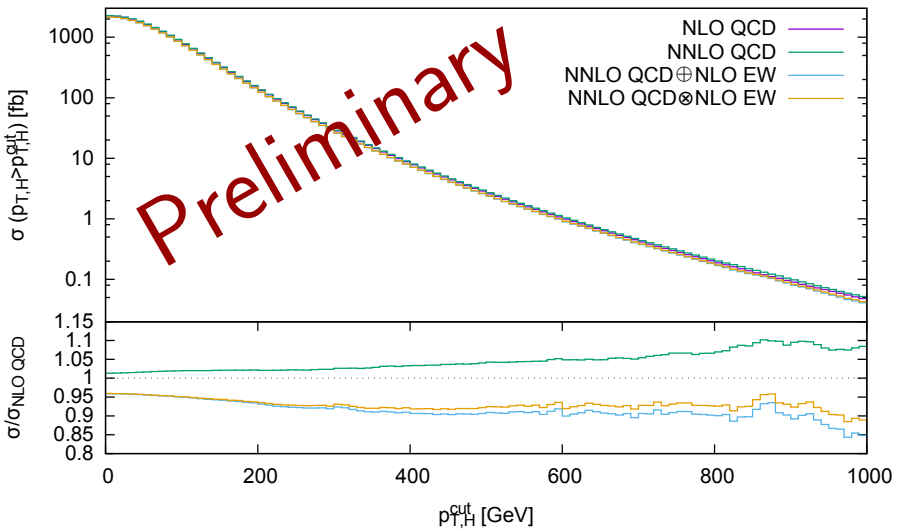
→ multi-jet merging

High Higgs Transverse Momentum

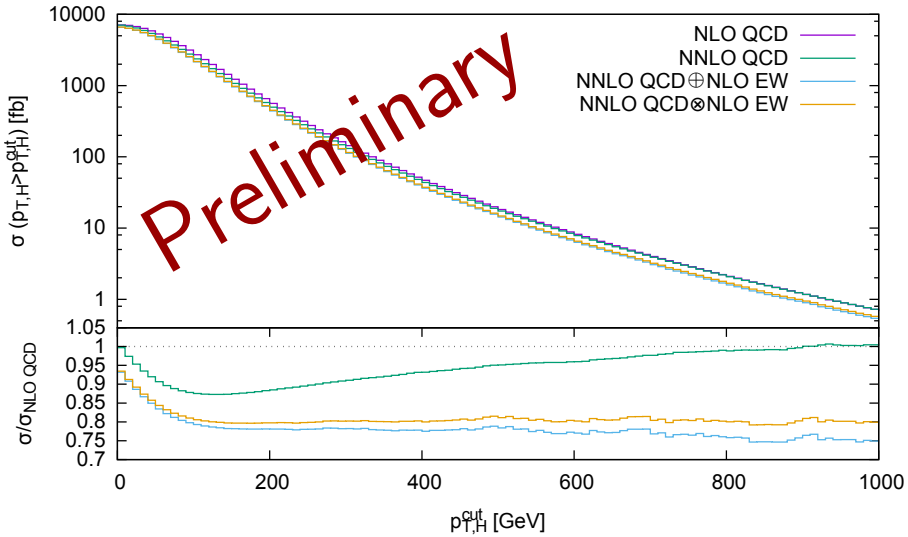
high transverse momentum region of Higgs starting to be studied [CMS HIG-17-010]

$\rightarrow$ need dedicated study of theory predictions

$\sqrt{S} = 13$ TeV



$\sqrt{S} = 27$ TeV



Roadmap

short term

- parton-shower accuracy
  - comparisons between different matched samples and different showering options
  - dedicated focus on central-jet veto
  - possibly new recommendations on central value and uncertainties to be adopted
- high-p_T Higgs boson
- cross sections for HE-LHC (27 TeV)
- Simplified Template Cross Sections uncertainty
  $\rightarrow$ preliminary results in experimental talk

medium & long term

- multi-jet merging of VBF-H+2jets and VBF-H+3jets
- QCD-induced *Hjj* background uncertainties
  - large contamination of theory uncertainties from *ggHjj* signal
  - *ggHjj* signal overestimated by current generators

  $\leftrightarrow$ ggF sub-group
- higher-order corrections plus parton shower (NNLOPS)

Twiki page: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGVBF

Parton-Shower Effects