VBF+VH group report

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for the VBF/VH WG1 sub-group

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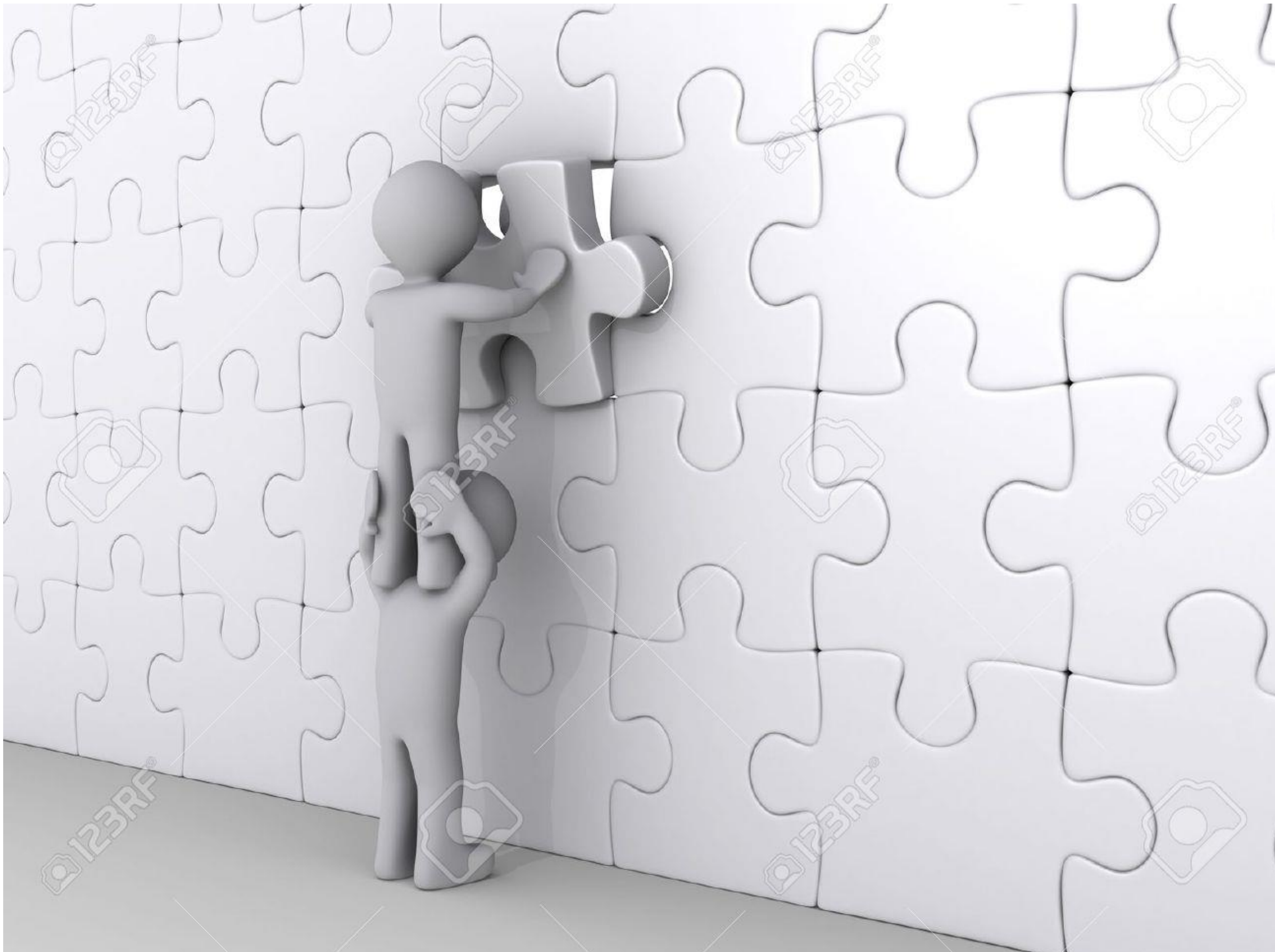
Updates since July



Brief reminder: general plan for the YR4

- VBF
  - H+2j – NNLO QCD total cross section/mass scan
    - Zaro et al. (VBFNNLO)
  - H+2j – NNLO QCD + NLO EWK fiducial/differential cross sections
    - Zanderighi, Cacciari, Salam et al. (QCD), Dittmaier et al. (EWK - HAWK)
  - H+3j – NLO QCD additional jet distributions
    - Jäger et al (POWHEG), Platzer, Figy et al (HERWIG, aka HJets++)
  - ggH+3j – NLO QCD central jet distributions for veto purpose [NOT INCLUDED]
    - Luisoni et al (GoSAM)
- VH
  - NNLO QCD + NLO EWK total/fiducial/differential cross sections
    - Tramontano et al. + Harlander et al. (QCD – HV@NNLO), Dittmaier et al (EWK – HAWK)
  - NNLO QCD differential cross sections
    - Campbell, Ellis, Williams (MCFM)
  - NLO QCD + PS differential cross sections for VH (including ggZH)
    - Papaefstathiou, Vryonidou , Frixione et al (MG5_aMC), Luisoni, Oleari et al (POWHEG)
  - NNLOPS differential cross sections
    - Re, Zanderighi et al (POWHEG)

A big thanks to all the authors!

Integrated VBF cross sections

The final VBF cross section σ^{VBF} is calculated according to:

$$\sigma^{\text{VBF}} = \sigma^{\text{DIS}}_{\text{NNLOQCD}}(1+\delta_{\text{EW}}) + \sigma_{\gamma}$$

Table 5.1: Total VBF cross sections including QCD and EW corrections and their uncertainties for different proton–proton collision energies $\sqrt{s}$ for a Higgs-boson mass $M_{\text{H}} = 125$ GeV.

$\sqrt{s}$[GeV]	σ^{VBF}[fb]	Δ_{scale}[%]	$\Delta_{\text{PDF}/\alpha_s/\text{PDF}\oplus\alpha_s}$[%]	$\sigma^{\text{DIS}}_{\text{NNLOQCD}}$[fb]	δ_{EW}[%]	σ_{γ}[fb]	$\sigma_{s\text{-channel}}$[fb]
7	1241.4(1)	$^{+0.19}_{-0.21}$	$\pm2.1/\pm0.4/\pm2.2$	1281.1(1)	-4.4	17.1	584.5(3)
8	1601.2(1)	$^{+0.25}_{-0.24}$	$\pm2.1/\pm0.4/\pm2.2$	1655.8(1)	-4.6	22.1	710.4(3)
13	3781.7(1)	$^{+0.43}_{-0.33}$	$\pm2.1/\pm0.5/\pm2.1$	3939.2(1)	-5.3	51.9	1378.1(6)
14	4277.7(2)	$^{+0.45}_{-0.34}$	$\pm2.1/\pm0.5/\pm2.1$	4460.9(2)	-5.4	58.5	1515.9(6)

Table 5.2: Fiducial VBF cross sections including QCD and EW corrections and their uncertainties for different proton–proton collision energies $\sqrt{s}$ for a Higgs-boson mass $M_{\text{H}} = 125$ GeV.

$$p_{\text{T},j} > 20\,\text{GeV}, \quad |y_j| < 5, \quad |y_{j_1} - y_{j_2}| > 3\,, \quad m_{jj} > 130\,\text{GeV}$$

$\sqrt{s}$[GeV]	σ^{VBF}[fb]	Δ_{scale}[%]	$\Delta_{\text{PDF}/\alpha_s/\text{PDF}\oplus\alpha_s}$[%]	$\sigma^{\text{DIS}}_{\text{NNLOQCD}}$[fb]	δ_{EW}[%]	σ_{γ}[fb]	$\sigma_{s\text{-channel}}$[fb]
7	602.4(5)	$^{+1.3}_{-1.6}$	$\pm2.3/\pm0.3/\pm2.3$	630.8(5)	-6.1	9.9	8.2
8	795.9(6)	$^{+1.3}_{-1.5}$	$\pm2.3/\pm0.3/\pm2.3$	834.8(7)	-6.2	13.1	11.1
13	1975.4(9)	$^{+1.3}_{-1.2}$	$\pm2.1/\pm0.4/\pm2.2$	2084.2(10)	-6.8	32.3	29.0
14	2236.6(26)	$^{+1.5}_{-1.3}$	$\pm2.1/\pm0.4/\pm2.1$	2362.2(28)	-6.9	36.7	33.1

Results for the VBF cross sections from a scan over the SM Higgs-boson mass M_{H} can be found in Appendix A.

Some discussion on the fiducial cuts, no universal choice (for instance when comparing with ggF studies)

VBF Process

- Cross sections are calculated at (approx.) NNLO QCD and NLO EW accuracies.
- Calculations are the same as CERN Report 3, except it is in NWA (CPS in CERN Report 3).
- Program: NNLO QCD (VBF@NNLO) and NLO EW (HAWK).
- QCD scales: $\mu=\mu_F=\mu_R=M_W$, uncertainty estimated in the range $1/2 < \mu/M_W < 2$ (keeping $\mu_F=\mu_R$).
    - No additional THU nor PU uncertainties assigned.
- PDF set: PDF4LHC15_nnlo_100 (QCD corrections) and NNPDF2.3QED (EW corrections + photon PDF)

m_H (GeV)	Cross Section (pb)	+QCD Scale %	-QCD Scale %	$\pm$(PDF+α_s) %	±PDF %	$\pm\alpha_s$ %
120.00	3.935E+00	+0.4	-0.3	±2.1	±2.1	±0.5
120.50	3.919E+00	+0.4	-0.3	±2.1	±2.1	±0.5
121.00	3.904E+00	+0.4	-0.3	±2.1	±2.1	±0.5

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Differential VBF cross sections

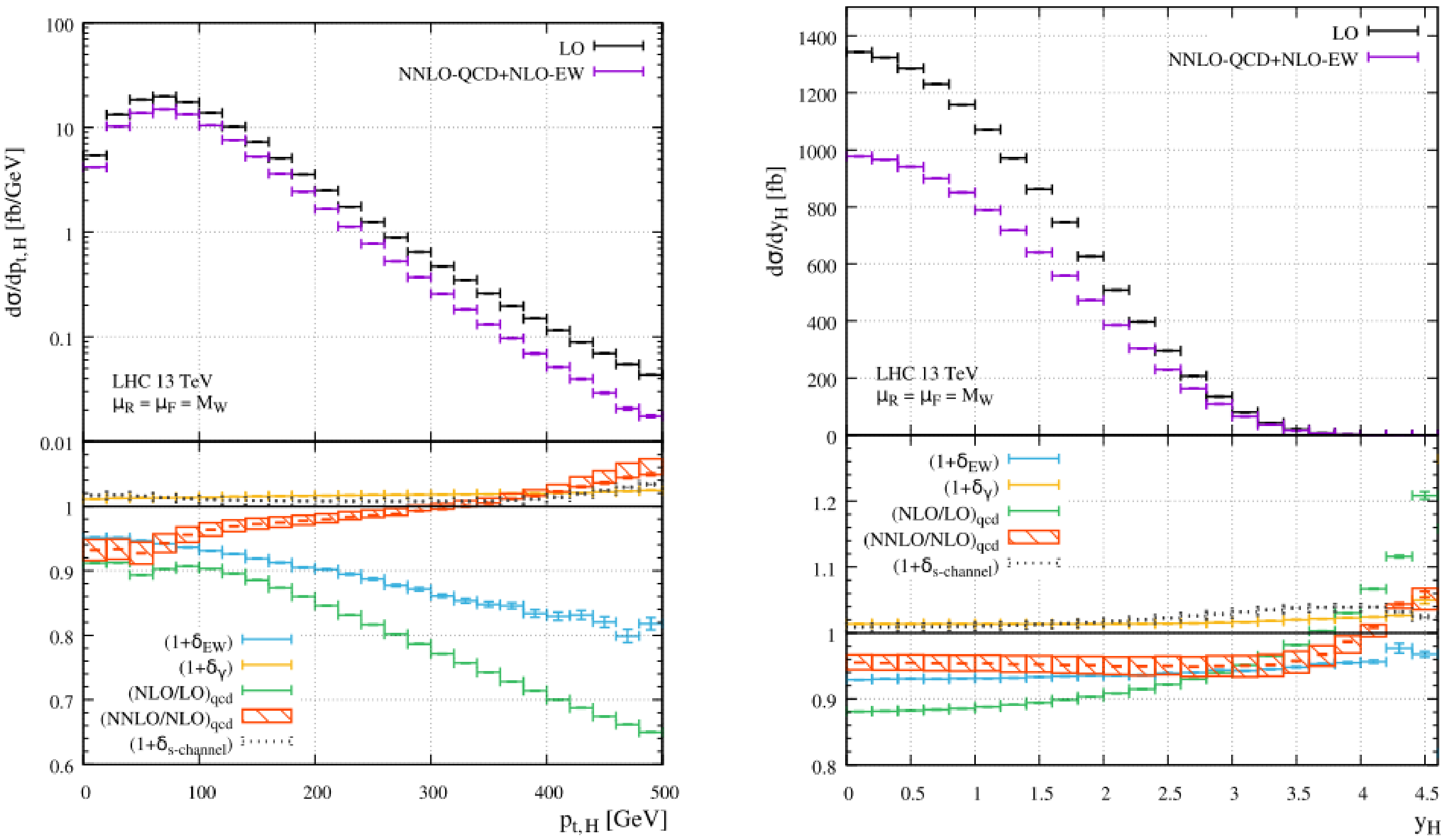

Fig. 1: Transverse-momentum and rapidity distributions of the Higgs boson in VBF at LO and including NNLO QCD and NLO EW corrections (upper plots) and various relative contributions (lower plots) for $\sqrt{s} = 13$ TeV and $M_H = 125$ GeV.

Total VH cross section

The total VH cross sections σ^{VH} are calculated according to

$$\sigma^{\mathrm{WH}} = \sigma^{\mathrm{WH,DY}}_{\mathrm{NNLOQCD}}(1+\delta_{\mathrm{EW}}) + \sigma_{\text{t-loop}} + \sigma_{\gamma}, \quad (5.15)$$

$$\sigma^{\mathrm{ZH}} = \sigma^{\mathrm{ZH,DY}}_{\mathrm{NNLOQCD}}(1+\delta_{\mathrm{EW}}) + \sigma_{\text{t-loop}} + \sigma_{\gamma} + \sigma^{\mathrm{ggZH}}, \quad (5.16)$$

Table 5.3: Total $\mathrm{W}^{+}(\to \mathrm{l}^{+}\nu_{\mathrm{l}})\mathrm{H}$ cross sections including QCD and EW corrections and their uncertainties for different proton–proton collision energies $\sqrt{s}$ for a Higgs-boson mass $M_{\mathrm{H}} = 125$ GeV.

$\sqrt{s}$[GeV]	σ[fb]	Δ_{scale}[%]	$\Delta_{\mathrm{PDF}/\alpha_s/\mathrm{PDF}\oplus\alpha_s}$[%]	$\sigma^{\mathrm{DY}}_{\mathrm{NNLOQCD}}$[fb]	$\sigma_{\text{t-loop}}$[fb]	δ_{EW}[%]	σ_{γ}[fb]
7	40.99	$^{+0.7}_{-0.9}$	$\pm1.9/\pm0.7/\pm2.0$	42.78	0.42	-7.2	$0.88^{+1.10}_{-0.10}$
8	49.52	$^{+0.6}_{-0.9}$	$\pm1.8/\pm0.8/\pm2.0$	51.56	0.53	-7.3	$1.18^{+1.38}_{-0.14}$
13	94.26	$^{+0.5}_{-0.7}$	$\pm1.6/\pm0.9/\pm1.8$	97.18	1.20	-7.4	$3.09^{+3.33}_{-0.37}$
14	103.63	$^{+0.3}_{-0.8}$	$\pm1.5/\pm0.9/\pm1.8$	106.65	1.36	-7.4	$3.55^{+3.72}_{-0.43}$

Table 5.5: Total ZH cross sections with $\mathrm{Z}\to \mathrm{l}^{+}\mathrm{l}^{-}$ including QCD and EW corrections and their uncertainties for different proton–proton collision energies $\sqrt{s}$ for a Higgs-boson mass $M_{\mathrm{H}} = 125$ GeV.

$\sqrt{s}$[GeV]	σ[fb]	Δ_{scale}[%]	$\Delta_{\mathrm{PDF}/\alpha_s/\mathrm{PDF}\oplus\alpha_s}$[%]	$\sigma^{\mathrm{DY}}_{\mathrm{NNLOQCD}}$[fb]	$\sigma^{\mathrm{ggZH}}_{\mathrm{NLO+NLL}}$[fb]	$\sigma_{\text{t-loop}}$[fb]	δ_{EW}[%]	σ_{γ}[fb]
7	11.43	$^{+2.6}_{-2.4}$	$\pm1.6/\pm0.7/\pm1.7$	10.91	0.94	0.11	-5.2	$0.03^{+0.04}_{-0.00}$
8	14.18	$^{+2.9}_{-2.4}$	$\pm1.5/\pm0.8/\pm1.7$	13.36	1.33	0.14	-5.2	$0.04^{+0.05}_{-0.00}$
13	29.82	$^{+3.8}_{-3.1}$	$\pm1.3/\pm0.9/\pm1.6$	26.66	4.14	0.31	-5.3	$0.11^{+0.12}_{-0.01}$
14	33.27	$^{+3.8}_{-3.3}$	$\pm1.3/\pm1.0/\pm1.6$	29.47	4.87	0.36	-5.3	$0.12^{+0.13}_{-0.01}$

Results for the total VH cross sections from a scan over the SM Higgs-boson mass M_{H} can be found in Appendix B.

WH Process

- Cross sections are calculated at NNLO QCD and NLO EW accuracies.
  - Calculations are the same as CERN Report 3, except photon-induced contribution (see below).
  - Total cross section is calculated from WH→lvH cross section by subtracting photon-induced cross section, and then scaled via BR(W→lv)=0.108535 in NLO EW accuracy.
- Program: NNLO QCD (VH@NNLO) and NLO EW (HAWK).
- QCD scales: $\mu=\mu_F=\mu_R=M_{VH}=(p_V+p_H)^2$ for QCD part and $\mu=\mu_F=\mu_R=M_{VH}+M_H$ for EW part. Uncertainty is estimated in the range $1/3 < \mu/M_{VH} < 3$ (μ_F and μ_R are varied independently).
  - No additional THU nor PU uncertainties assigned.
- PDF set: PDF4LHC15_nnlo_mc (QCD part) and NNPDF2.3QED (EW part).
- Photon-induced contribution of O(5%)
  - NOT included for total cross section (agrees with CERN Report 3 numbers within 1%).
  - Included in cross sections for dedicated WH→lvH (l=e,μ or τ) process (we strongly recommend to use these numbers for dedicated analyses).

m_H (GeV)	Cross Section (pb)	+QCD Scale %	-QCD Scale %	±(PDF+α_s) %	±PDF %	±α_s %	W^+H (pb)	W^-H (pb)
120.00	1.565E+00	+0.5	-0.6	±1.8	±1.6	±0.9	9.558E-01	6.092E-01
120.50	1.545E+00	+0.5	-0.7	±1.8	±1.6	±0.9	9.439E-01	6.007E-01
121.00	1.524E+00	+0.5	-0.7	±1.8	±1.7	±0.9	9.320E-01	5.925E-01

⋮

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ZH Process

- Cross sections are calculated at NNLO QCD and NLO EW accuracies.
  - Calculations are the same as CERN Report 3, except photon-induced contribution (see below).
  - Total cross section is calculated from ZH→llH,ννH cross sections by subtracting photon-induced cross section, and then scaled via BR(Z→ll)=0.0335962 and BR(Z→νν)=0.201030 in NLO EW accuracy.
  - gg→ZH (box-diagram) occurs as a part of NNLO QCD correction and included in the total cross section.
  - ZH cross section went up by +1~2%, due to +22~16% for $\sqrt{s}$ = 7-14 TeV, due to increase in gg→ZH for NLO+NLL QCD corrections (NLO in CERN Report 3).
- Program: NNLO QCD (VH@NNLO) and NLO EW (HAWK).
- QCD scales: $\mu=\mu_F=\mu_R=M_{VH}=(p_V+p_H)^2$ for QCD part and $\mu=\mu_F=\mu_R=M_{VH}+M_H$ for EW part. Uncertainty is estimated in the range $1/3 < \mu/M_{VH} < 3$ (μ_F and μ_R are varied independently).
  - No additional THU nor PU uncertainties assigned.
- PDF set: PDF4LHC15_nnlo_mc (QCD part) and NNPDF2.3QED (EW part).
- Photon-induced contribution of O(1%) or below
  - NOT included for total cross section (agrees with CERN Report 3 numbers).
  - Included in cross sections for dedicated ZH→llH,ννH (l=e,μ or τ) processes (we strongly recommend to use these numbers for dedicated analyses).

m_H (GeV)	Cross Section (pb)	+QCD Scale %	-QCD Scale %	±(PDF+α_s) %	±PDF %	±α_s %	σ(gg→ZH) (pb)
120.00	9.939E-01	+3.4	-3.0	±1.6	±1.3	±1.0	1.299E-01
120.50	9.829E-01	+3.4	-3.0	±1.6	±1.3	±1.0	1.292E-01
121.00	9.705E-01	+3.5	-3.0	±1.6	±1.3	±1.0	1.281E-01

⋮

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Fiducial VH cross sections

Table 5.7: Fiducial $W^{+}(\rightarrow l^{+}\nu_{l})H$ cross sections including QCD and EW corrections and their uncertainties for proton–proton collisions at $\sqrt{s} = 13\text{TeV}$ for a Higgs-boson mass $M_{H} = 125$ GeV.

$\sqrt{s}$[GeV]	σ[fb]	$\Delta_{\text{scale}}[\%]$	$\Delta_{\text{PDF}}[\%]$	$\sigma^{\text{DY}}_{\text{NNLOQCD}}$[fb]	$\delta_{\text{EW}}[\%]$	σ_{γ}[fb]
13	73.90	$^{+0.3}_{-0.3}$	± 1.4	78.61	-8.3	$1.81^{+1.10}_{-0.23}$

Table 5.8: Fiducial $W^{-}(\rightarrow l^{-}\bar{\nu}_{l})H$ cross sections including QCD and EW corrections and their uncertainties for proton–proton collisions at $\sqrt{s} = 13\text{TeV}$ for a Higgs-boson mass $M_{H} = 125$ GeV.

$\sqrt{s}$[GeV]	σ[fb]	$\Delta_{\text{scale}}[\%]$	$\Delta_{\text{PDF}}[\%]$	$\sigma^{\text{DY}}_{\text{NNLOQCD}}$[fb]	$\delta_{\text{EW}}[\%]$	σ_{γ}[fb]
13	42.77	$^{+0.2}_{-0.3}$	± 1.8	45.29	-8.0	$1.11^{+0.65}_{-0.12}$

Table 5.9: Fiducial ZH cross sections with $Z \rightarrow l^{+}l^{-}$ including QCD and EW corrections and their uncertainties for proton–proton collisions at $\sqrt{s} = 13\text{TeV}$ for a Higgs-boson mass $M_{H} = 125$ GeV.

$\sqrt{s}$[GeV]	σ[fb]	$\Delta_{\text{scale}}[\%]$	$\Delta_{\text{PDF}}[\%]$	$\sigma^{\text{DY}}_{\text{NNLOQCD}}$[fb]	σ^{ggZH}[fb]	$\delta_{\text{EW}}[\%]$	σ_{γ}[fb]
13	16.08	$^{+2.2}_{-1.4}$	± 1.2	16.21	1.36	-9.2	0.00

Differential VH cross sections

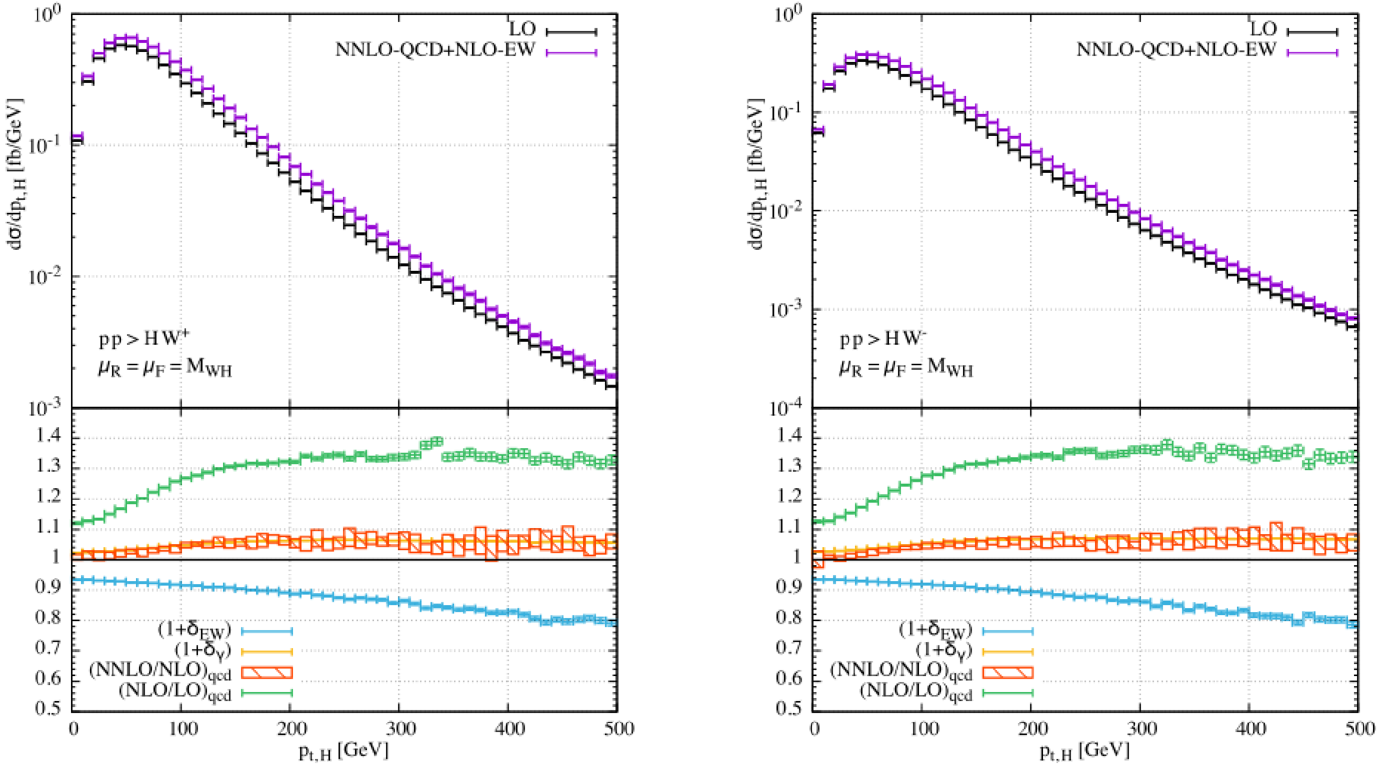

Fig. 8: Left: transverse-momentum distributions of the Higgs boson in W^+H production at LO and including NNLO QCD and NLO EW corrections (upper plots) and relative higher-order contributions (lower plots) for $\sqrt{s} = 13$ TeV and $M_H = 125$ GeV. Right: the same for W^-H production. Note that δ_γ is based on the central value of the photon PDF of NNPDF2.3qed, while σ_γ in Tables 5.3–5.9 is based on combined results using the median and the photon PDF of MRST2004qed (and smaller by a factor 0.7), see text.

Differential VH cross sections

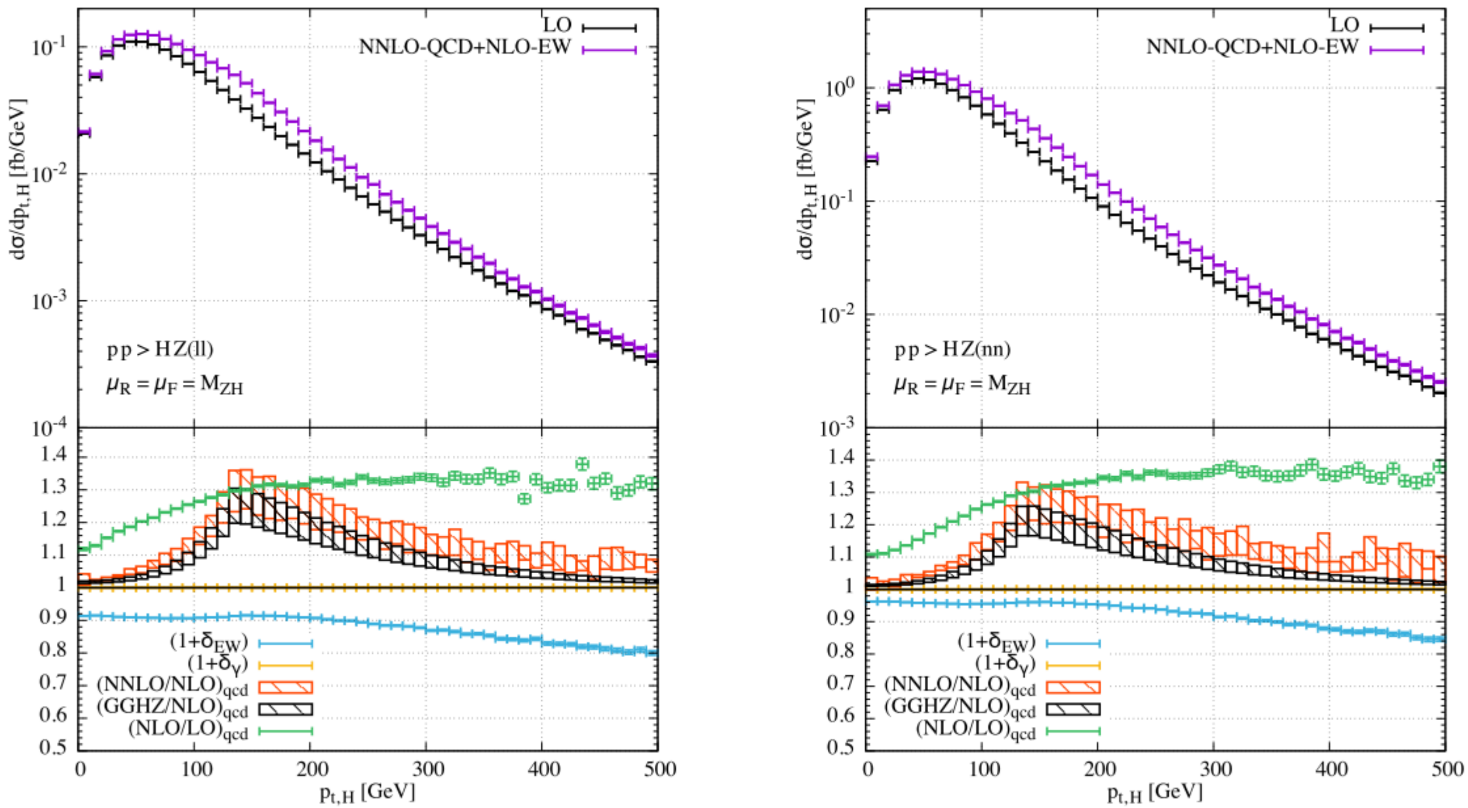

Fig. 13: Left: transverse-momentum distributions of the Higgs boson in $Z(\rightarrow l^+l^-)H$ production at LO and including NNLO QCD and NLO EW corrections (upper plots) and relative higher-order contributions (lower plots) for $\sqrt{s} = 13$ TeV and $M_H = 125$ GeV. Right: the same for $Z(\rightarrow \nu\bar{\nu})H$ production.

NLO k-factor for ggZH known to be ~2, not included

H+3j production through VBF at NLO+PS

- Study complementary to the ggH 3rd jet studies
  - cfr presentation from A. Massironi

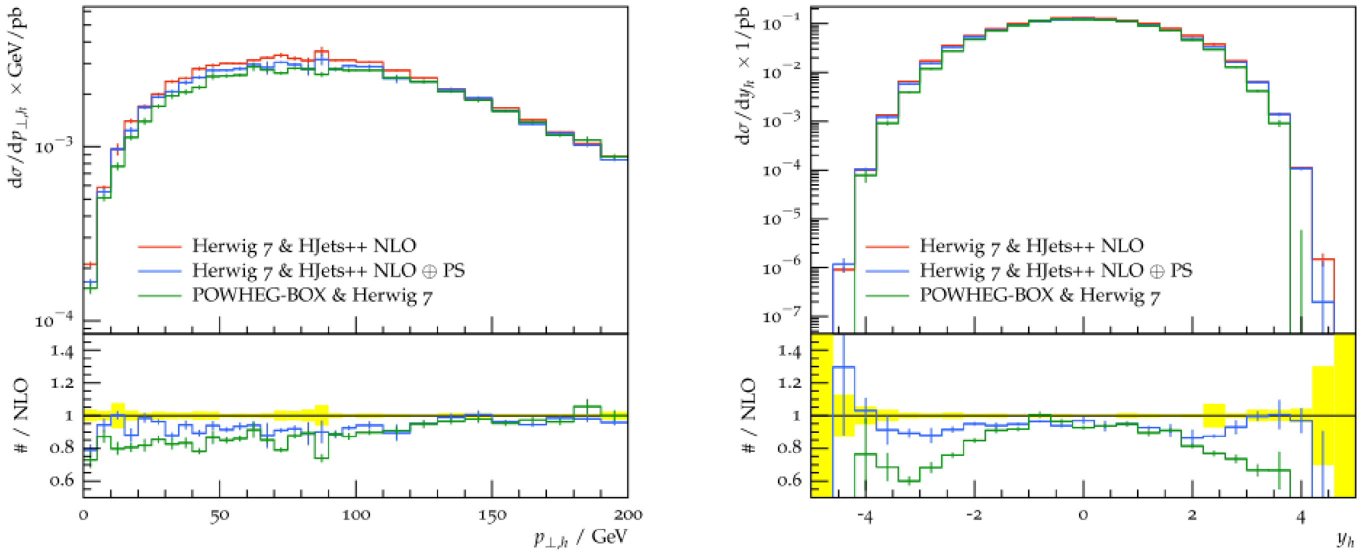

Fig. 21: Transverse-momentum and rapidity distributions of the Higgs boson in EW H+3 jet production at NLO QCD (red line) as obtained from using the Matchbox framework of HERWIG7 with the HJets++ plugin, and at NLO QCD matched with the HERWIG7 angular ordered parton shower in the same framework (blue line), and with the POWHEG BOX (green line), respectively. The lower panels show the respective ratios of the NLO+PS to the fixed-order NLO QCD result for $\sqrt{s} = 13$ TeV and $M_H = 125$ GeV. The yellow bands indicate the statistical uncertainty of the NLO result.

H+3j EWK production at NLO+PS

- Some residual differences when matching to PS compared to fixed order calculations

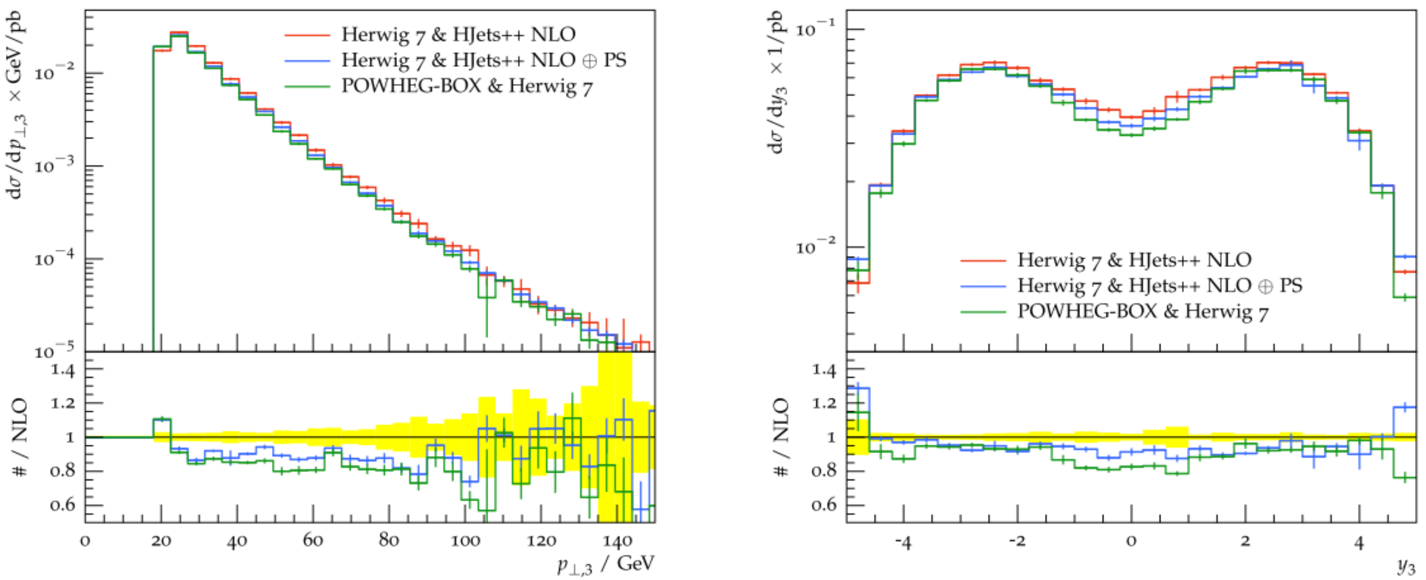

Fig. 23: Transverse-momentum and rapidity distributions of the third jet in EW H+3 jet production at NLO QCD (red line) as obtained from using the Matchbox framework of HERWIG7 with the HJets++ plugin, and at NLO QCD matched with the HERWIG7 angular ordered parton shower in the same framework (blue line), and with the POWHEG BOX (green line), respectively. The lower panels show the respective ratios of the NLO+PS to the fixed-order NLO QCD result for $\sqrt{s} = 13$ TeV and $M_H = 125$ GeV. The yellow bands indicate the statistical uncertainty of the NLO result.

VH production at NLO+PS

- Higgs left undecayed
- Important differences due to different parton shower choices
- Further enhanced when including Higgs decay (to be addressed in future studies)

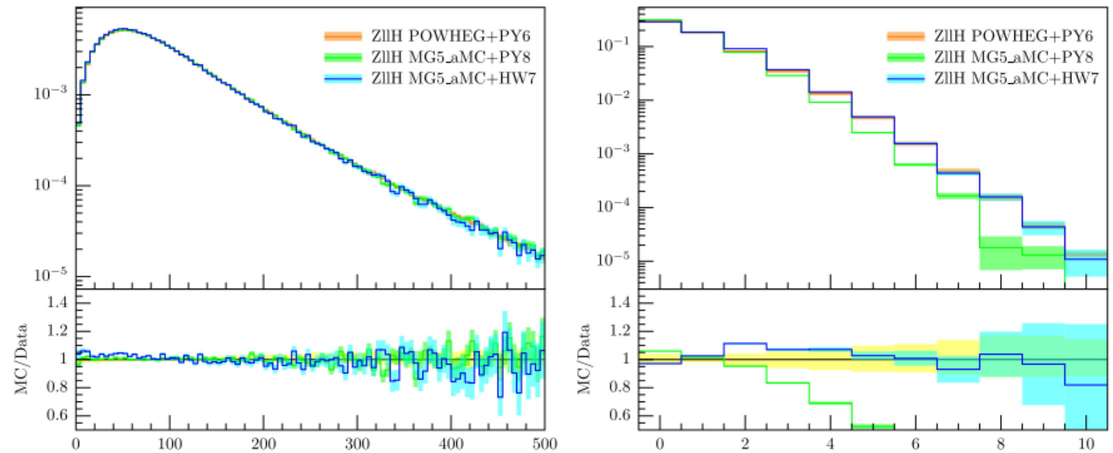

Fig. 24: Comparison of the boson p_T (left) and number of additional jets (right) in the inclusive case for $Z(ll)H$.

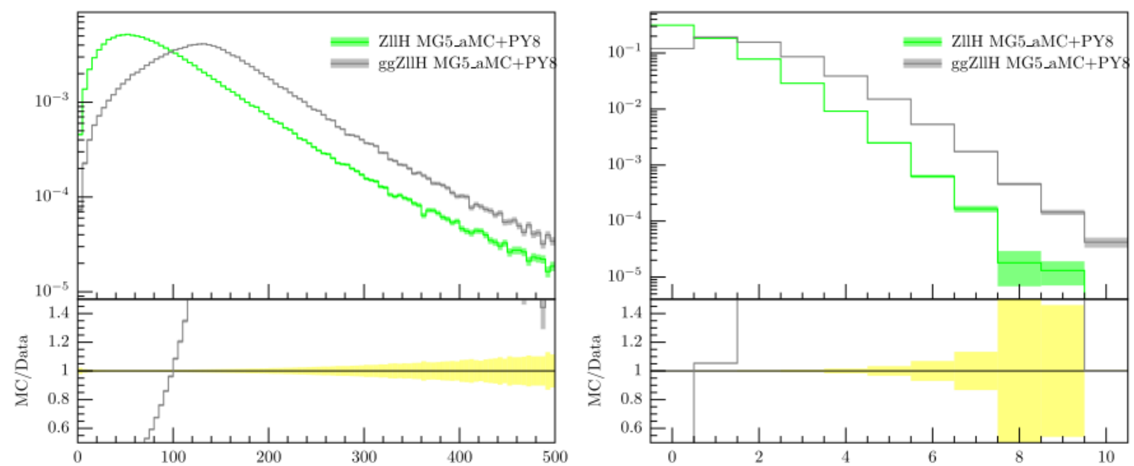

Fig. 28: Comparison of the boson p_T (left) and number of additional jets (right) in the inclusive case for $Z(ll)H$.

NNLOPS for HW+

$$pp \to HW^+ \to Hl^+\nu_l \tag{5.28}$$

For the process in eq. (5.28) the Born kinematics is fully specified by 6 independent variables. We have chosen them to be: the transverse momentum of Higgs boson ($p_{\mathrm{T,H}}$); the rapidity of HW system (y_{HW}); the difference of Higgs rapidity and the W^+ rapidity (Δy_{HW}); the invariant mass of $e^+\nu_e$ system ($m_{e\nu}$); and the two Collins-Soper angles (θ^*, ϕ^*) [154]:

$m_{e\nu}$ has a flat k-factor

Sizeable reduction of the uncertainty band when HWJ-MINLO results are upgraded to NNLOPS

Differences arise at low p_T(HW) between fixed order NNLO and NNLOPS due to resummation

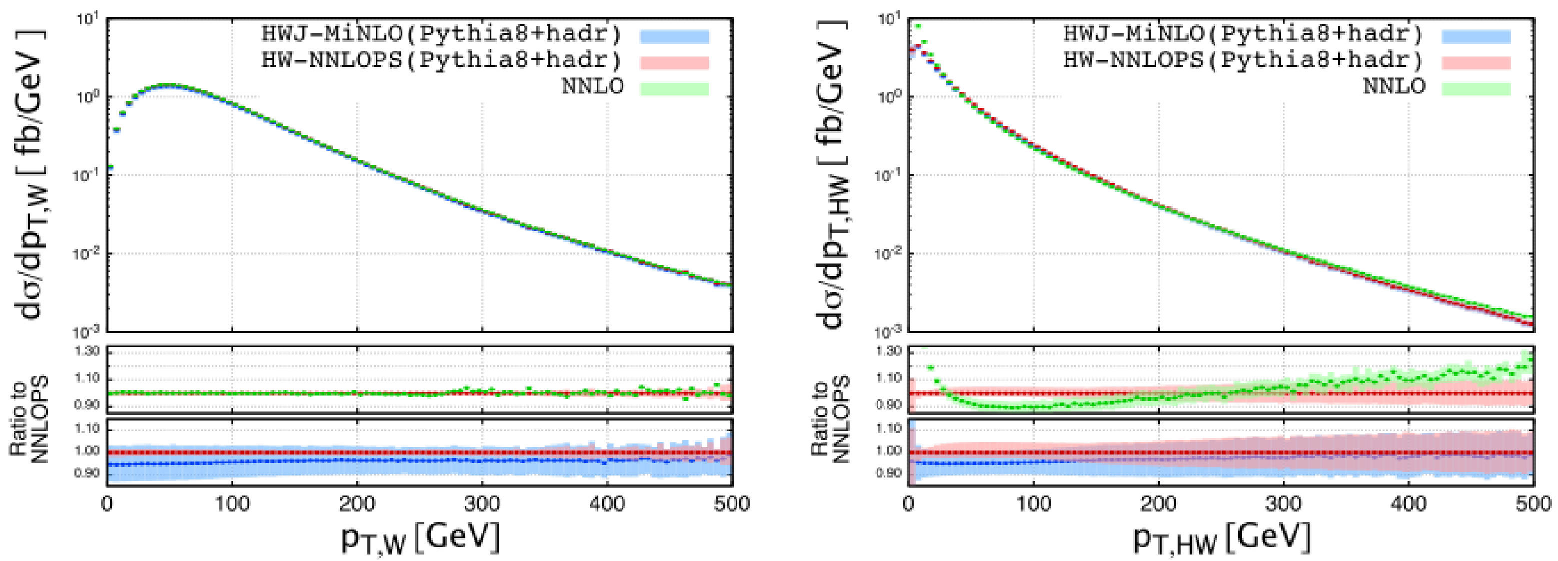

Fig. 30: Comparison of HWJ-MINLO (PYTHIA8+HADR) (blue), NNLO (green), and HW-NNLOPS (PYTHIA8+HADR) (red) for $p_{\mathrm{T,W}}$ (left) and $p_{\mathrm{T,HW}}$ (right).

NNLOPS for HW+

- In Fig. 31 there are large differences among the NNLO result and those containing Sudakov resummation: expected, since large-rapidity jets have smaller transverse momentum, where NNLO is singular

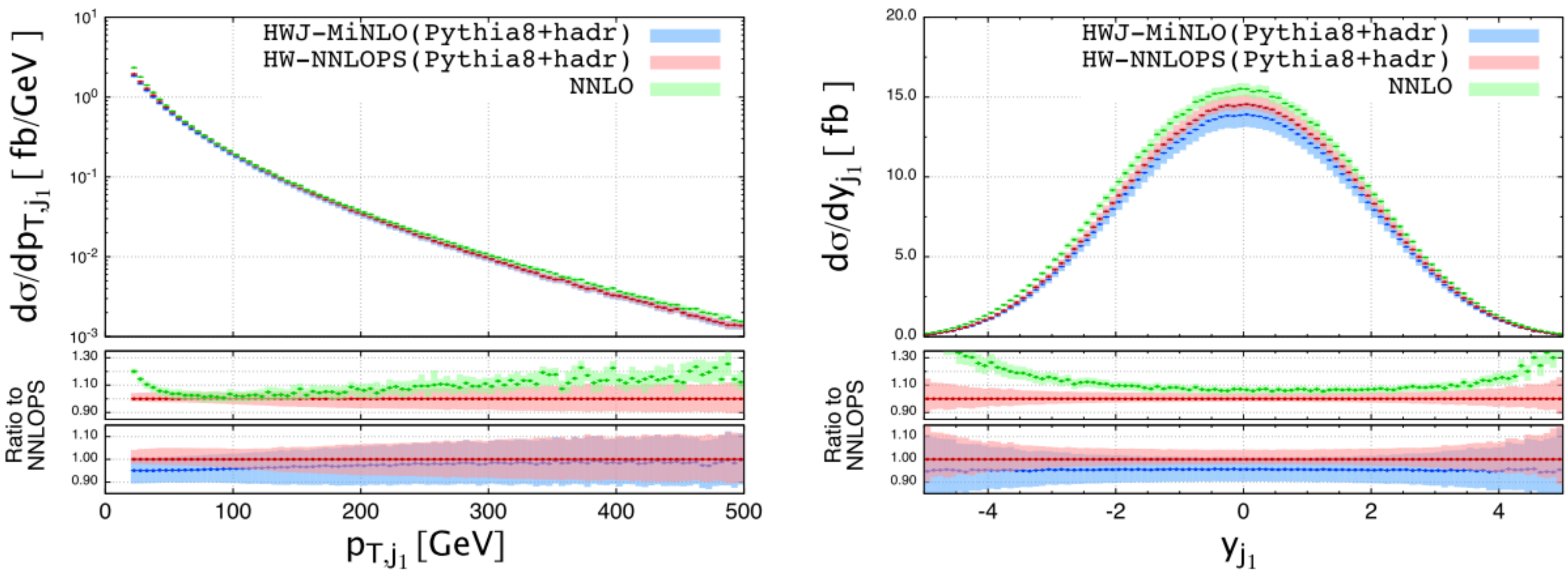

Fig. 31: Comparison of HWJ-MiNLO (PYTHIA8+HADR) (blue), NNLO (green), and HW-NNLOPS (PYTHIA8+HADR) (red) for $p_{\mathrm{T},\mathrm{j}_1}$ (left) and y_{j_1} (right).

Residual issues / wishlist for VH+VBF

VBF

1) Central Jet Veto
   - CJV definition used by experimental collaboration may not be trivial (third jet information as input for MVA)
   - third jet in VBF described at LO in MC sample currently used by experimental collaborations
   - compare third jet kinematics of VBF Hjj NLO with VBF Hjjj NLO. Differences covered by scale uncertainties?
2) VBF NNLO reweighting
   - Experiments interested in profiting of higher order calculations (NNLO QCD + NLO EWK) to reweight available MC samples
     - Usually 1D reweighting performed
     - Discussions ongoing to choose the most appropriate variable and phase space
3) Consistent combination of POWHEG VBF H+2j and VBF H+3j not yet possible

VH

1) As for VBF case, experiments interested in profiting of higher order calculations (NNLO QCD + NLO EWK) to reweight available MC samples
   - In run1, a 1D reweighting was performed on the boson pT (in 2 jet bins) since this variable is used to categorize events in the analyses
   - Other variables like ΔRbb being discussed and considered
   - Long term awaited solution is NNLOPS VH, embedding multidimensional reweighting to NNLO QCD and smaller uncertainties
2) Alternative recipes being discussed for the ggZH uncertainty after inclusive NLO k-factor reweighting
   - More conservative (likely too much): assign full ggZH correction
   - More aggressive: assign absolute LO scale variations instead of relative ones (might need to reweight differentially)

1) Studies with ggH

2) Discussions

3) Longer term plan

1) NNLOPS WH available

2) Propagation of LO MC relative uncertainty

Prospects for the VH/VBF group (I)

- Future physics goals:
  - The SM cross-section central values are not expected to change significantly within the span of the 13 TeV data taking
  - N^3LO inclusive in the VBF case available since Summer '16 (**arXiv:1606.00840**). Although small correction, differential calculations will bring to a further narrowing of the uncertainties, which then will be dominated by pdf and α_s
    - For all WG1 subgroups it is essential to receive a consistent input-parameter set + instructions on PDFs, etc.
    - Requires centralized coordination for all subgroups
  - The NNLO event generation might become of interest to compare to differential measurements, to study the additional radiation emission besides the two VBF jets in an environment which might be cleaner than VBF Z or W production
  - Future generations (Sherpa, Madgraph) might include EWK and QCD corrections together
  - Thorough comparisons of the existing fixed order and NLO+PS VH calculations with NNLOPS including the Higgs decay

Prospects for the VH/VBF group (II)

Other considerations:

- The discussion of all these studies and the consistent collection of their results are greatly enhanced by the existence of a working group that keeps track and coordinates the "down on Earth" work, to continue comparing and validating the calculations in specific phase space as part of the 13 TeV studies.
  - Important to coordinate common theoretical issues with other sub-groups

- Possible extensions of the working group go in the direction of taking charge of the VBF and VH related issues also in the BSM cases addressed by the Higgs XSWG, exploiting the same benefits that this group brings to the SM case
  - Goal: bring XS predictions in BSM models to the same level of accuracy as in the SM
  - Centralized coordination needed for
    - specific BSM models (input-parameter schemes, renormalization, benchmarks, etc.)
    - effective field theories (operator bases, benchmarks, etc.)

- The PDFs are an important consideration for the experiments, and we plan to actively participate in the forthcoming discussions about the PDF4LHC15 implementations and related topics.

Timeline for future VH+VBF activities

- **Short term plan (say till Moriond '17):**
  - VH
    - Finalize/validate/crosscheck the recipe for differential QCD+EWK signal corrections
    - Finalize the study of matrix element + parton shower signal comparisons including Higgs decay to b-bbar, using the existing Rivet analysis
  - VBF
    - Re-weighting of NLO+PS to NNLO differential distribution
- **medium term plan (say till Summer '17 or Moriond '18):**
  - VH
    - Extend the matrix element + parton shower comparison in the di-bjet final state to diboson and drell yan (for drell yan, compare LO vs NLO, 4F vs 5F, etc)
  - VBF
    - NNLOPS for VBF process
  - VH+VBF
    - try to quantify expected systematic uncertainties due to parton shower differences and other effects, try to provide some recommendations
- **long term plan:**
  - VH
    - increase sinergy with anomalous couplings studies and BSM in general
  - VBF
    - merging of VBF +2jet NLO and VBF + 3jets NLO

Backup

VH/VF contributions to YR4