VBF+VH group report

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for the VBF/VH WG1 sub-group

LHC Higgs Cross Section Working Group Assembly
CERN, January 14th, 2016

General plan for the YR4

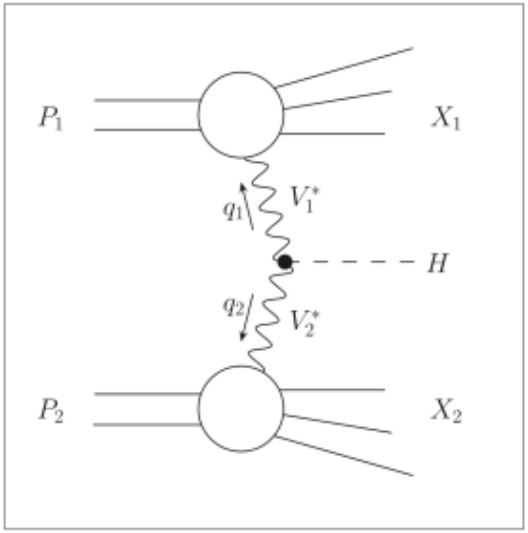
- Last meeting called on Jan 8th to check the status of the ongoing activities https://indico.cern.ch/event/476326/

- 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
    - 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
  - NLO QCD differential cross sections
    - Frixione et al (aMC@NLO), Luisoni et al (POWHEG), ATLAS+CMS (aMC@NLO+POWHEG)
  - ggZH differential cross sections
    - Vryonidou et al. (Madgraph), ATLAS+CMS (aMC@NLO+POWHEG)
  - NNLOPS differential cross sections
    - Re, Zanderighi et al (POWHEG)


VBF

Features of VBF QCD corrections

- Compute QCD corrections in the structure function approach: VBF = DIS^2



- Contributions which do not obey factorisations estimated to be negligible (<10% of NNLO correction)
- Include interferences at LO ($\leq$0.5%)

VBF: SM cross sections at NNLO QCD + NLO EW

The plan:

Update of total and fiducial state-of-the-art SM cross sections

for $\sqrt{s} = 7, 8, 13, 14\,\text{TeV}$ and $M_\text{H} = 120.0, 120.1, ...125.0, 125.09, ...130.0\,\text{GeV}$ for SM

Cuts for the fiducial XS:

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

Note: Cut on m_{jj} quite loose to maximize available phase space
$\hookrightarrow$ effects of harder cuts can be read from distributions

Scale choice: $\mu_\text{R} = \mu_\text{F} = M_\text{W}$ (dyn. scale better?)

State-of-the-art XS:

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

$\sigma^\text{DIS}_\text{NNLOQCD}$: based on Cacciari et al., arXiv:1506.02660
(+ Bolzoni et al., arXiv:1003.4451 for total XS)

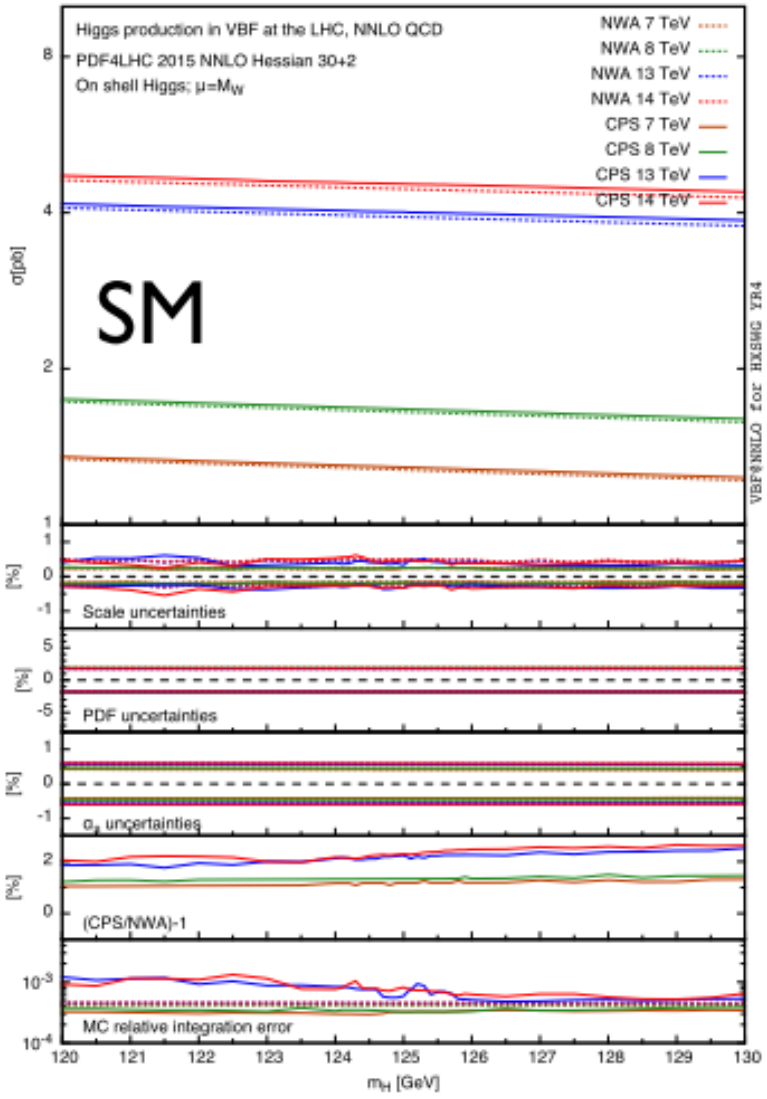
δ_EW, σ_γ: calculated with HAWK (Denner et al.)

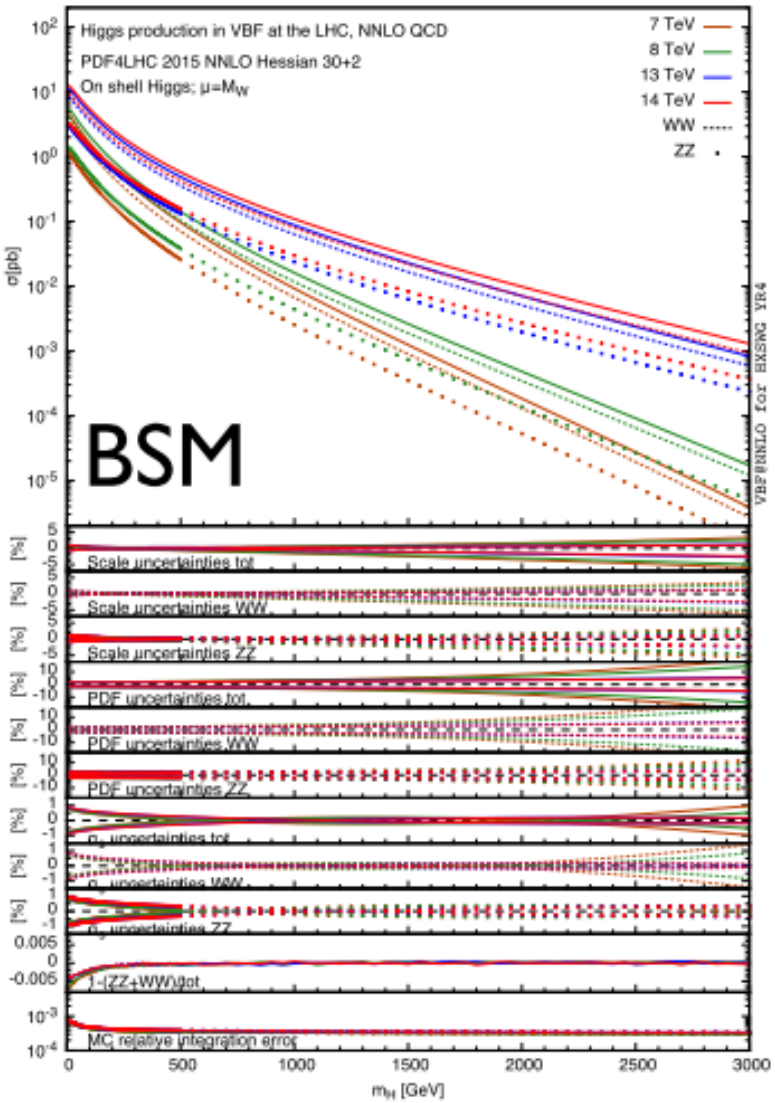
VBF@NNLO

Bolzoni, Maltoni, Moch, Zaro, arXiv:1003.4451 & arXiv:1109.3717

- Input parameters as in LHCHXSWG-INT-2015-006
- PDF4LHC NNLO, Hessian error estimate, 30+2 sets (PDF+α_S)
- $\mu_F=\mu_R=m_W$; independent variations of a factor 2
- Mass scan:
  - SM Higgs case: $m_H \in$ [120 GeV, 130 GeV]
    - σ computed with H on shell and in the CPS
  - BSM Higgs case: $m_H \in$ [10 GeV, 3000 GeV]
    - σ computed with H on shell
    - WW and ZZ separate contributions (no LO interference)
- $\sqrt{s}$=7,8,13,14 GeV

Results





All numbers and uncertainties included in the YR4

NNLO QCD results by Cacciari et al.

Integrated VBF XS: (Full scan over $\sqrt{s}$ and M_{H} values $\rightarrow$ appendix of YR4)

Total XS:

$\sqrt{s}$[GeV]	σ^{VBF}[fb]	Δ_{scale}[%]	$\Delta_{\mathrm{PDF}\oplus\alpha_{\mathrm{s}}}$[%]	$\sigma^{\mathrm{DIS}}_{\mathrm{NNLOQCD}}$[fb]	δ_{EW}[%]	σ_γ[fb]	$\sigma_{s\text{-chan}}$[fb]
7	1241.4(1)	$^{+0.19}_{-0.21}$	± 2.2	1281.1(1)	-4.4	17.1	584.5(3)
8	1601.2(1)	$^{+0.25}_{-0.24}$	± 2.2	1655.8(1)	-4.6	22.1	710.4(3)
13	3781.7(1)	$^{+0.43}_{-0.33}$	± 2.1	3939.2(1)	-5.3	51.9	1378.1(6)
14	4277.7(2)	$^{+0.45}_{-0.34}$	± 2.1	4460.9(2)	-5.4	58.5	1515.9(6)

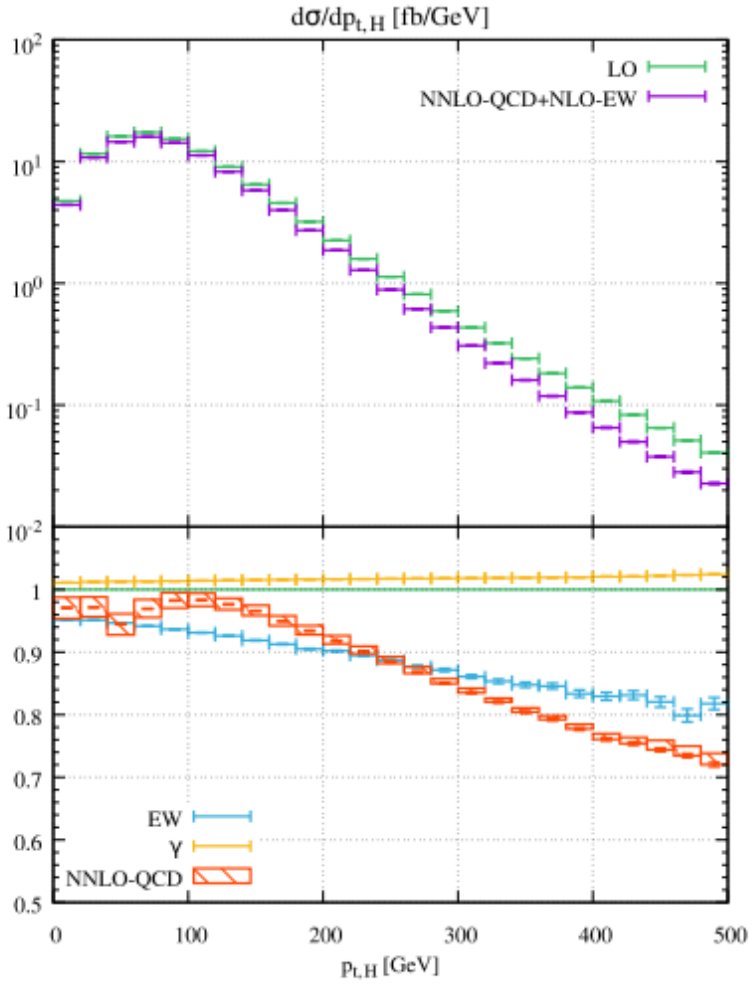
Fiducial XS:

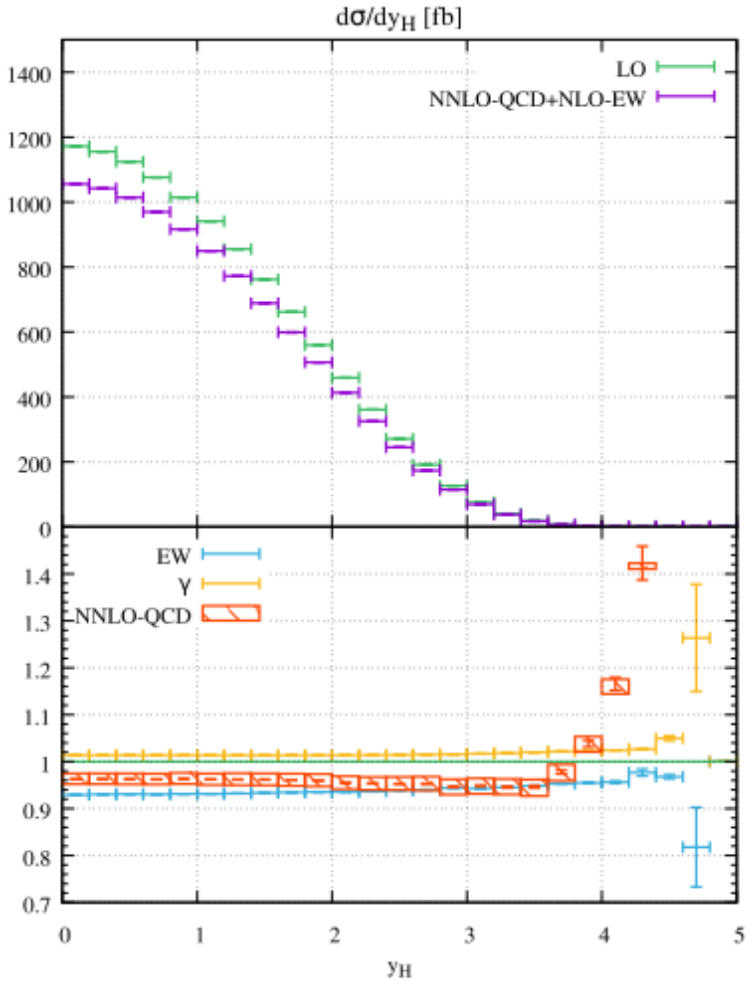
$\sqrt{s}$[GeV]	σ^{VBF}[fb]	Δ_{scale}[%]	$\Delta_{\mathrm{PDF}\oplus\alpha_{\mathrm{s}}}$[%]	$\sigma^{\mathrm{DIS}}_{\mathrm{NNLOQCD}}$[fb]	δ_{EW}[%]	σ_γ[fb]	$\sigma_{s\text{-chan}}$[fb]
7	602.4(5)	$^{+1.3}_{-1.6}$	± 2.3	630.8(5)	-6.1	9.9	8.2
8	795.9(6)	$^{+1.3}_{-1.5}$	± 2.3	834.8(7)	-6.2	13.1	11.1
13	1975.4(9)	$^{+1.3}_{-1.2}$	± 2.2	2084.2(10)	-6.8	32.3	29.0
14	2236.6(26)	$^{+1.5}_{-1.3}$	± 2.1	2362.2(28)	-6.9	36.7	33.1

- contribution σ_γ from $q\gamma$ channels $\sim 1.5\%$ with large uncertainty
  $\hookrightarrow$ does NOT decrease with tighter VBF cuts!
- s-channel contribution $\sigma_{s\text{-chan}}$ not included in σ^{VBF}, but given for reference
  $\hookrightarrow$ does decrease with tighter VBF cuts!

NNLO QCD results by Cacciari et al.

Differential VBF XS: (still preliminary)

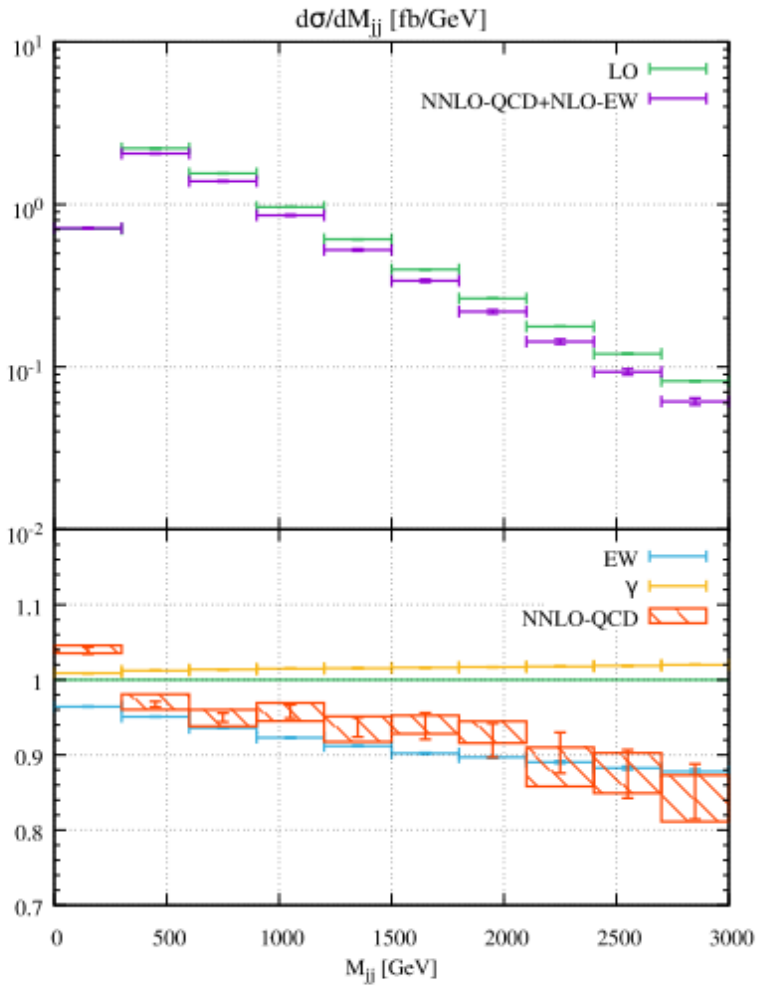


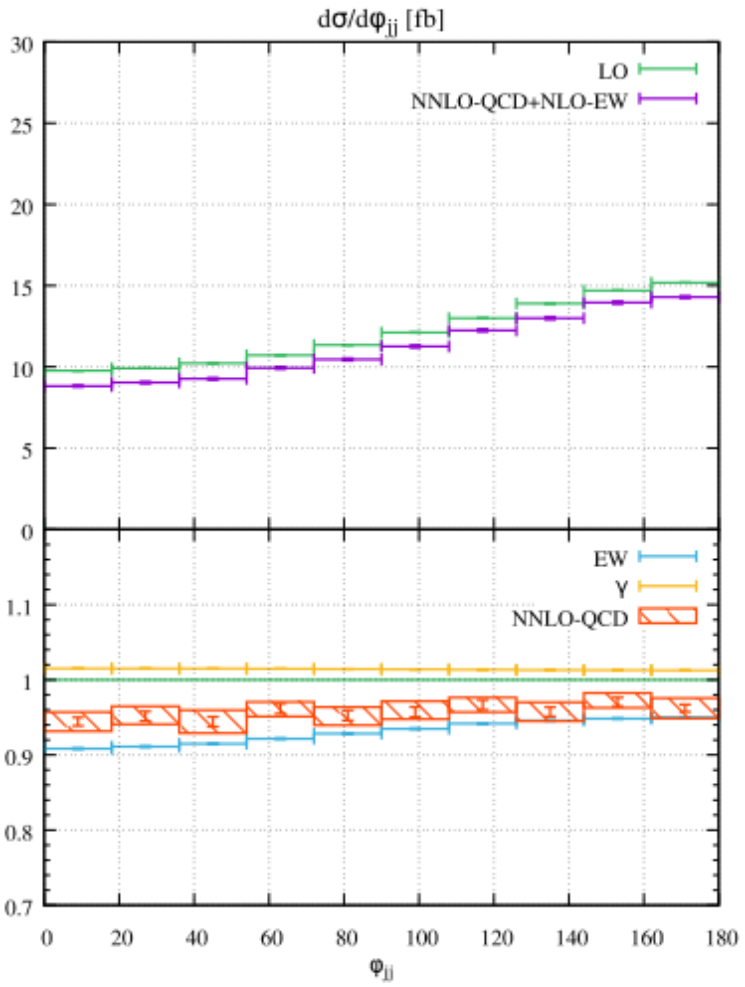


Special thanks to A.Karlberg!

NNLO QCD results by Cacciari et al.

Differential VBF XS: (still preliminary)





Special thanks to A.Karlberg!

powerful tool for background suppression: central jet veto

central jet veto (CJV):

remove events with extra jet(s) in central-rapidity region

$$p_T^{\text{veto}} > 20 \text{ GeV}, \eta_{\text{jet}}^{\text{min}} < \eta_{\text{jet}}^{\text{veto}} < \eta_{\text{jet}}^{\text{max}}$$

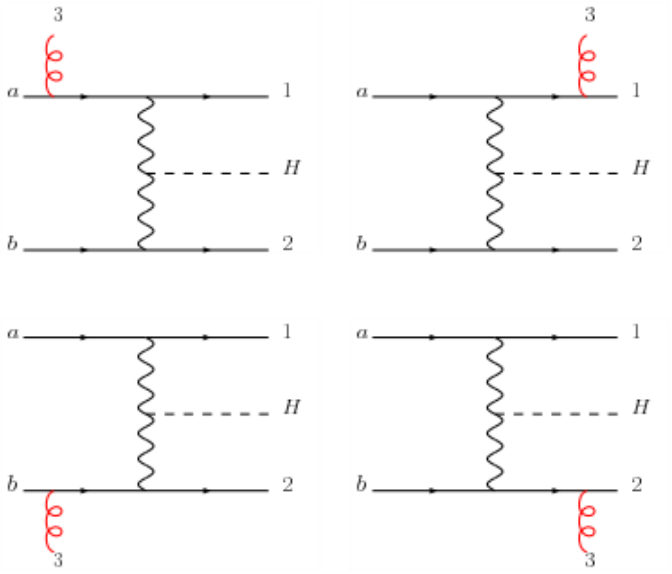
little effect on VBF signal, but strong suppression of backgrounds

$\rightarrow$ improvement of S/B by ca. factor of 4

- Need to ensure precise description of additional jet for both signal and backgrounds
  - Comparisons ongoing

$pp \to Hjjj$ via VBF

$$\mathcal{M}_B(Hjjj) \leftrightarrow \mathcal{M}_R(Hjj)$$



Figy, Hankele, Zeppenfeld (2007):

NLO-QCD in VBF approximation

(no color exchange between upper/lower quark lines, no VH-type contributions)

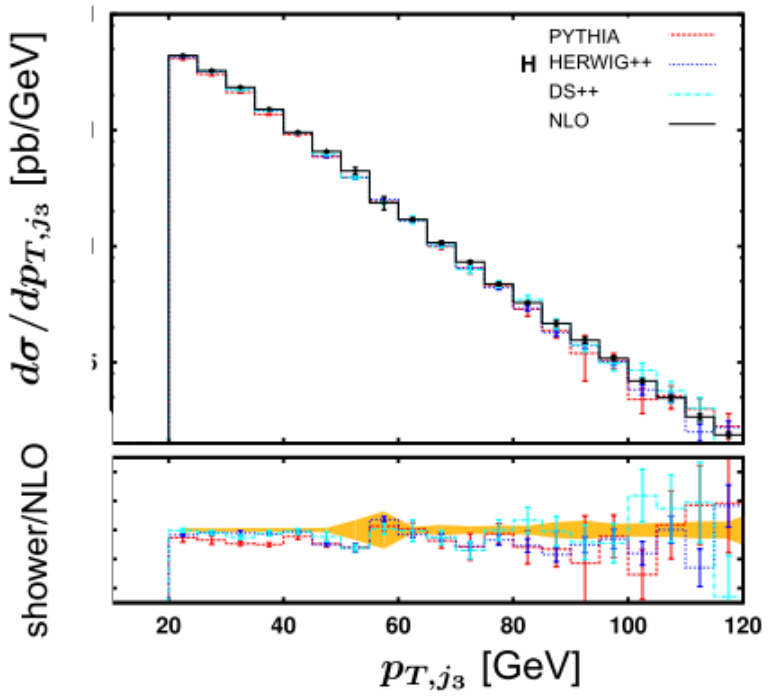
Campanario, Figy, Plätzer, Sjödahl (2013):

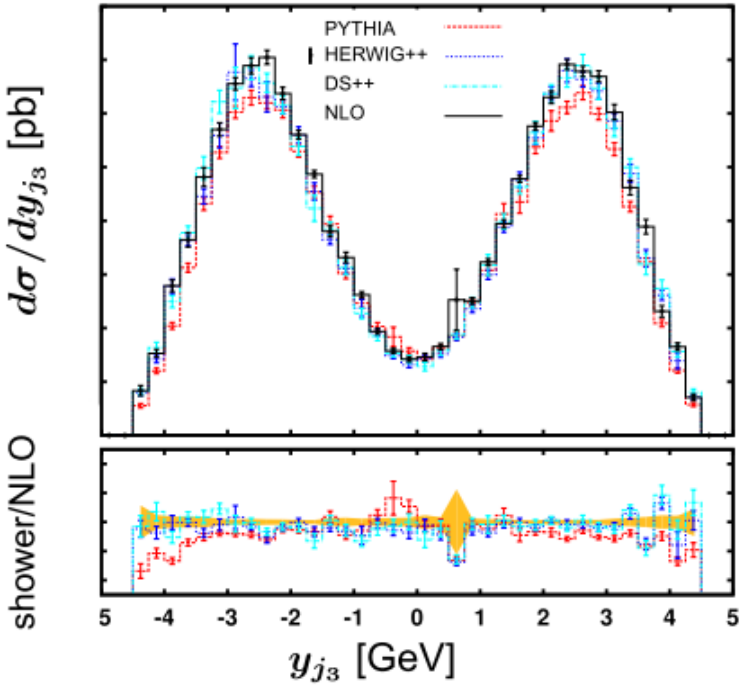
full NLO-QCD calculation

(good agreement with approximative calculation)

$pp \to Hjjj$ via VBF and parton shower @ NLO QCD

Schissler, Zeppenfeld, B.J. (2014)



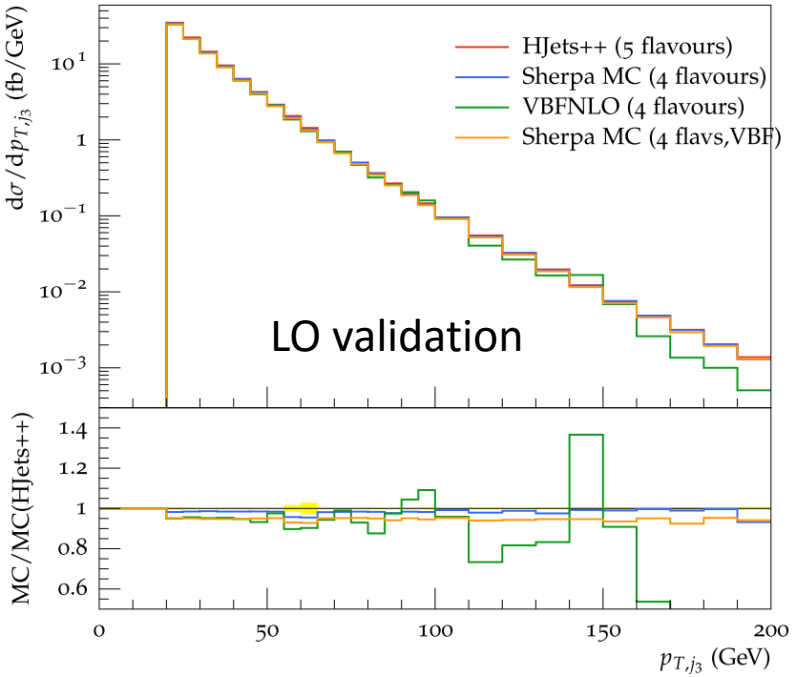


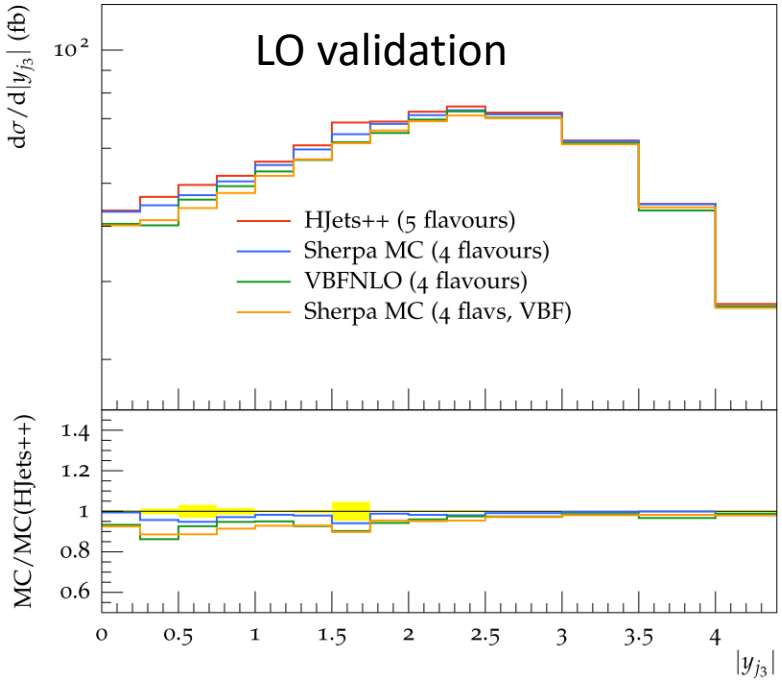
VBF $Hjjj$ matrix elements at NLO combined with parton shower

$\to$ description of 3rd jet well under control

$pp \to Hjjj$ via VBF and parton shower @ NLO QCD

- Alternative calculations at NLO (currently LO validation performed)
  - Herwig, also known as HJets++
  - VBFNLO
  - SHERPA (full and t-channels only)
- Setup
  - CM energy: 13 TeV, PDF: CTEQ10nlo_nf4, anti-kt R=0.4 jets
  - Required ≥3 jets with $p_T > 20$ GeV and $|y_{jet}| < 5$
  - Events cuts: rapidity gap $|\Delta y_{j1,j2}| > 3$ and $m_{j1,j2} > 130$ GeV





ggH contamination in VBF

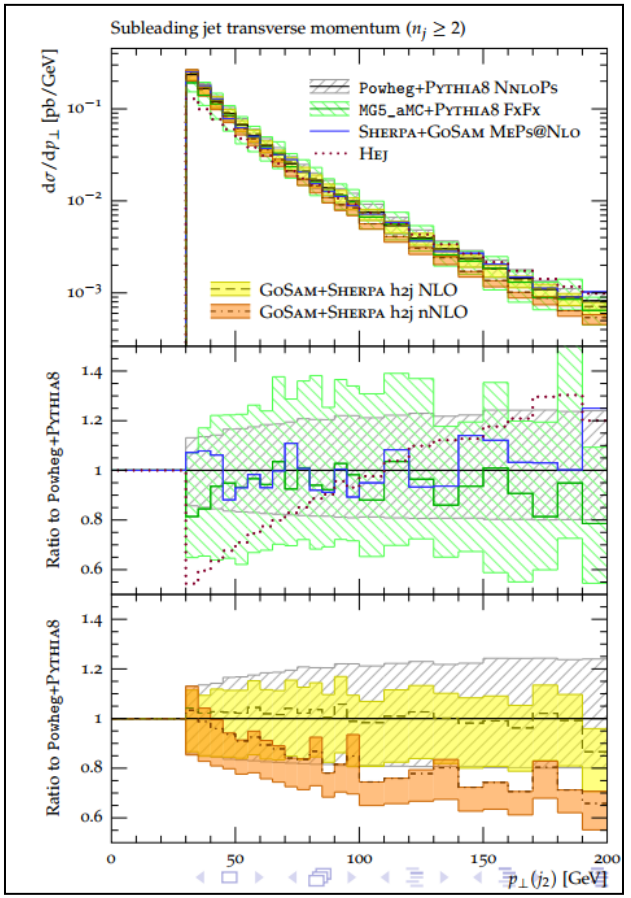
- Interesting studies performed for H+2j in the context of Les Houches H+jets studies, presented by Marek yesterday [*]
- Joint ggF + VH/VBF meeting being planned to follow up on VBF specific needs (3rd jet kinematics for central jet veto)

Parton-shower matched & multijet merged

- K. Becker (ATLAS) $pp \to h$ NNLOPS
  POWHEG-BOX+PYTHIA8 ✓
- S. Höche $pp \to h$ UN^{2}LOPS
  SHERPA ✗
- R. Frederix, E. Vryonidou $pp \to h + 0, 1, 2j$@NLO
  MG5_aMC+PYTHIA8 ✓
- J. Bellm, S. Plätzer, P. Schichtel $pp \to h + 0, 1, 2j$@NLO
  HERWIG7+MADGRAPH5+OPENLOOPS ✗
- S. Höche, M. Schönherr $pp \to h + 0, 1, 2, 3j$@NLO, $4, 5j$@LO
  SHERPA+GOSAM (✓)

BFKL resummation

- J. Andersen $pp \to h +$ jets
  HEJ (✓)



[*] http://indico.cern.ch/event/407347/session/3/contribution/26/attachments/1210940/1766591/LH15-hjets.pdf

Residual issues / wishlist

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

VH: SM cross sections at NNLO QCD + NLO EW

The plan:

Update of total and fiducial state-of-the-art SM cross sections with W/Z decays for $\sqrt{s} = 7, 8, 13, 14\,\text{TeV}$ and $M_\text{H} = 120.0, 120.1, ...125.0, 125.09, ...130.0\,\text{GeV}$

Cuts for the fiducial XS:

$$p_{\text{T},\ell} > 15\,\text{GeV}, \quad |y_\ell| < 2.5, \qquad \text{for Z} \to \ell\ell\text{:} \quad 75\,\text{GeV} < M_{\ell\ell} < 105\,\text{GeV}$$

State-of-the-art XS:

$$\sigma^{\text{VH}} = \sigma^{\text{DY}}_{\text{NNLOQCD}}\,(1 + \delta_{\text{EW}}) + \sigma^{\text{non-DY}}_{\text{NNLOQCD}} + \sigma_{\text{gg}} + \sigma_\gamma$$

$\sigma^{\cdots}_{\text{NNLOQCD}}$: total XS: `vh@nnlo` (Harlander et al.)
diff. XS: Ferrera et al., arXiv:1107.1164, arXiv:1405.4827, `MCFM` (Campbell et al.), arXiv:1601.00658

σ_{gg}: total NLO XS: Altenkamp et al., arXiv:1211.5015,
diff. XS: NLO unknown , LO available from POWHEG and Madgraph
(recipe: K-factor from total XS, but keep LO relative uncertainties)

δ_{EW}, σ_γ: calculated with `HAWK` (Denner et al.)

VH NLO tools comparisons

- Quantify the level of agreement of available codes
- Define phase space for Z(ll)H, ggZ(ll)H W(lν), Z(νν)H, use same distributions for the 3 channels, provide Rivet analysis to easily combine results

Z(ll)H(bb)

- Z p_T bins: inclusive, [0-100 GeV], (100 GeV-200 GeV], >200 GeV
- leptons: $|\eta| < 2.5$, $p_T > 15$ GeV
- m_{ll} in range [75-105 GeV]

Z(vv)H(bb)

- Z p_T bins: inclusive, [0-150 GeV], (150 GeV-250 GeV], >250 GeV

W(lv)H(bb)

- W p_T bins: inclusive, [0-150 GeV], (150 GeV-250 GeV], >250 GeV
- leptons: $|\eta| < 2.5$, $p_T > 15$ GeV

Additional jet counting

- Additional jets count if $p_T > 20$ GeV and $|\eta| < 4.5$

Proposed plots (histograms) for Yellow Report 4

100 bins each

- 0 < pT_H < 500 (a)
- -5 < y_H < 5 (b)
- 0 < pT_lepton < 500 (c)
- 0 < pT_nu/nubar < 500 (d)
- -5 < y_lepton < 5 (e)

For the other 5 plots above (a-e) we are going to produce 4 sets of plots:

- one set inclusive over pT_W/Z and
- one set for each of the 3 pT_W/Z bins reported on the wiki page.

The plot below (1) can be produced for the inclusive case only

- 0 < pT_W/Z < 500 (1)

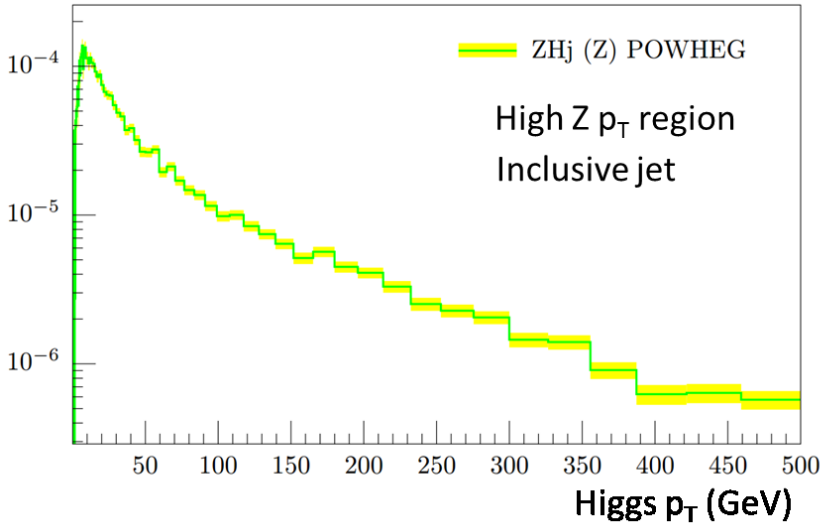
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGVHYR4
https://github.com/perrozzi/rivet_analysis_VH_YR4

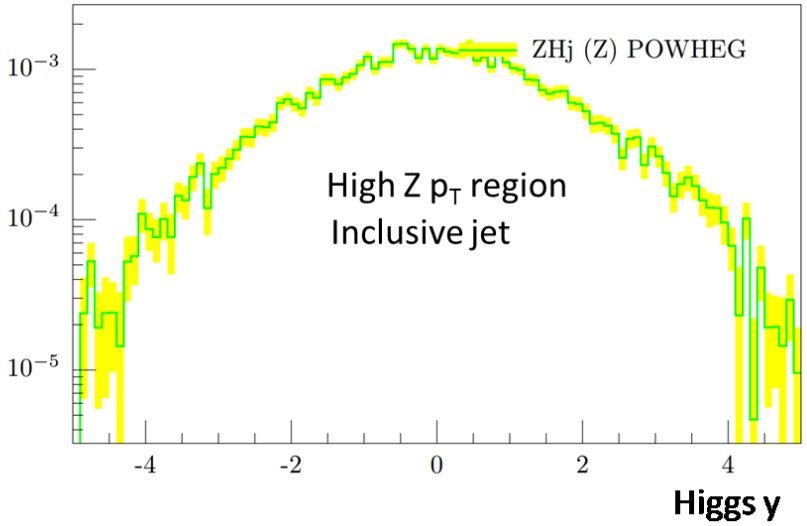
VH NLO tools comparisons

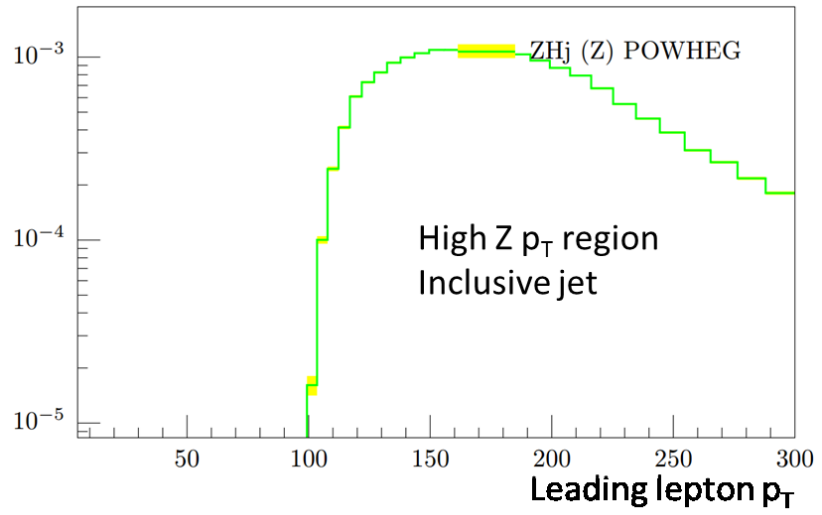
- Groups/collaboration expressing interest
  - NLO QCD differential cross sections
    - Frixione et al (aMC@NLO+Pythia/Herwig), Luisoni et al (POWHEG+Pythia6)
  - ggZH differential cross sections
    - Vryonidou et al. (Madgraph)
- Effort originally driven by theorists
  - But both ATLAS and CMS collaborations are interested to compare their setup and distributions

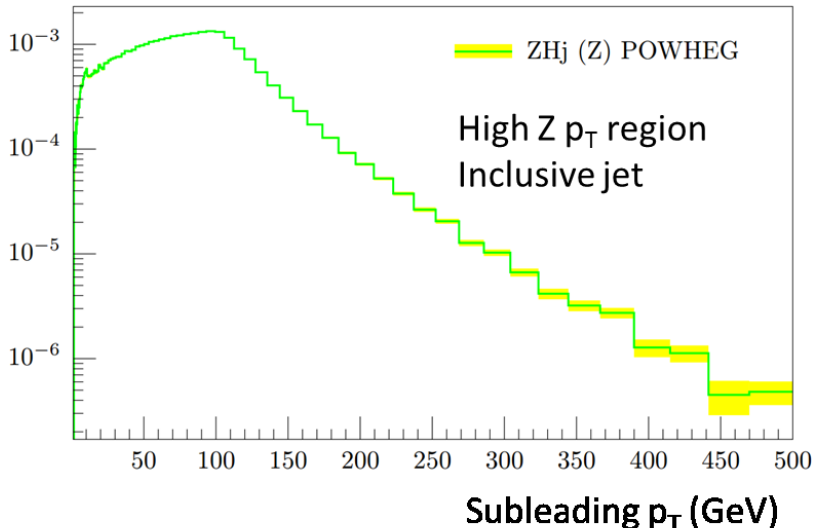
VH NLO tools comparisons

- Preliminary results provided by POWHEG+Pythia6 (no hadronization)



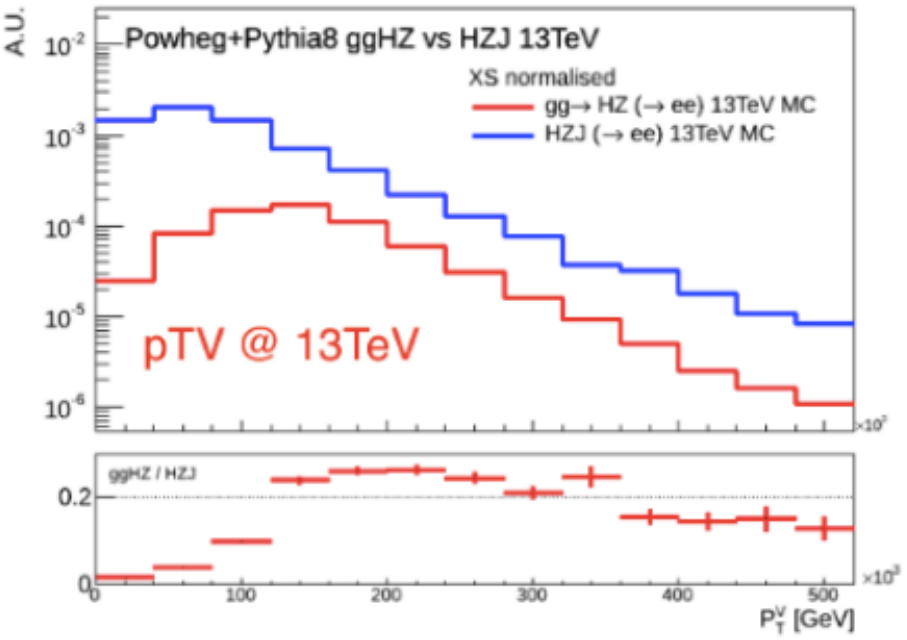


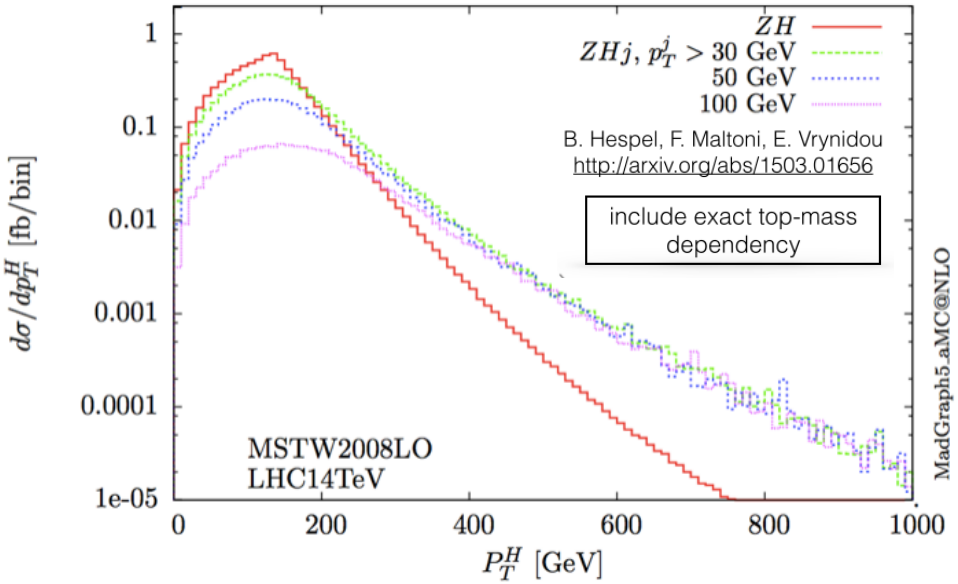




The ggZH process

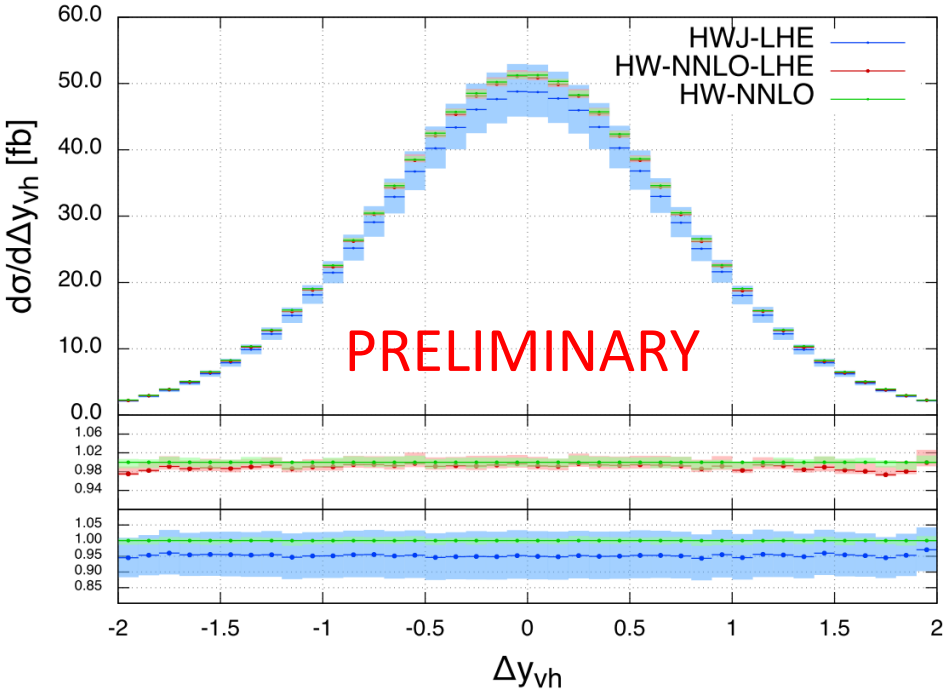
- gg- initiated ZH processes start to contribute at NNLO
  - Large cross section increase (x4) from 8 TeV to 13 TeV
  - gg/qq increasing in the VH(bb) searching region (V p_T > 150 GeV)
  - Large inclusive NLO k-factor ~2 computed
  - LO MC tools provided by POWHEG and Madgraph (also merged with 1j)
  - Direct comparison important to asses the level of agreement between the 2 codes

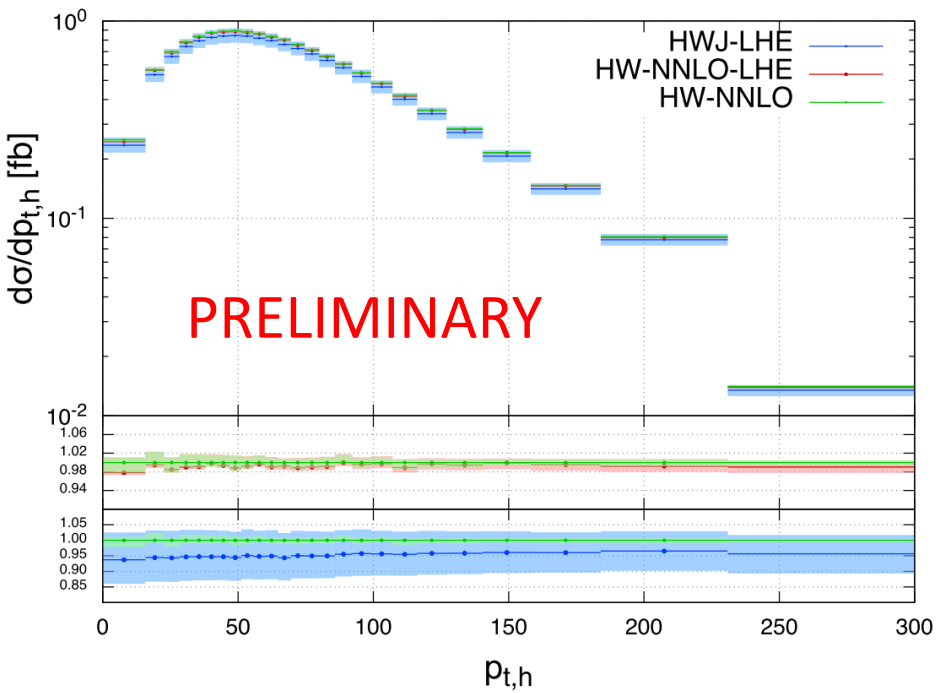




NNLO+PS for HW production

- **Work in progress** (Zanderighi et al., plots thanks to W. Astill and W. Bizon)
- Method used based on MiNLO+POWHEG :
  - Underlying MiNLO simulation from Luisoni,Nason,Oleari,Tramontano, '13
  - NNLO from Ferrera,Grazzini,Tramontano, '11-'13
  - The approach is similar to the NNLOPS for Higgs and Drell-Yan case
  - Number of reweightings reduced from the original 5d (details not yet publicly available)
- **Preliminary validation plots**: Higgs pt , rapidity difference WH
  - Label "-LHE" stands for hard partonic events (after MiNLO and after MiNLO+NNLO reweighting, but before parton shower)





Residual issues / wishlist

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)

Conclusions

- Quite rich program of comparisons ongoing for both VBF and VH, targeting the YR4 deadlines
  - Most of the activities are in advanced state
  - Some coordination with ggF subgroup will be started for the comparison of ggH process in VBF phase space
  - We are thankful to the various groups for the tremendous effort
- YR4 text in good shape, we will add results as they will be provided
- Few residual issues to be discussed in the next weeks

Backup