VH/VBF modelling in ATLAS

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VH/VBF modelling in ATLAS

This talk will cover the studies for VH and VBF Monte Carlo prediction for Run2 ATLAS analyses, from the generators and setting adopted to the points open for discussions and improvement.

- **ATLAS VH & VBF Higgs analyses** (quick overview of where these production modes are the most important in ATLAS)

- **VH associated production**
  - MC generators studied: Powheg, aMC@NLO
  - EFT benchmark with aMC@NLO
  - Fixed order predictions
  - Systematic uncertainties and corrections

- **VBF vector boson fusion**
  - MC modelling of VBF and VBF+γ
  - Systematic uncertainties
  - ggF contamination in VBF signal regions
  - BSM scenarios and reweighting

- **Conclusion and wishlist**

VH/VBF analyses in ATLAS

Associated production mechanism in ATLAS:

- **VH→Vbbar** (http://arxiv.org/abs/1409.6212)
- VH→VWW (ATLAS-CONF-2013-075)
- Analysis category in other channels (γγ, WW, ZZ)
- Sensitive to high-pT Higgs boson production (pT>200GeV)
- [significant for Vhbb thanks to the large BR(bb)]

pb	8 TeV	13 TeV	ratio
ggF	19	44	2.3
VBF	1.6	3.7	2.3
VH	1.1	2.2	2
ttH	0.13	0.5	3.8

Several analyses are sensitive to the VBF production mode:

- H→WW, γγ, ZZ, ττ
- Especially important for ττ: the dominant contribution to the **H→ττ** evidence comes from the VBF analysis category

$$\hat{\mu}^{\tau\tau}_{\mathbf{ggF}} = 1.93^{+0.78}_{-0.77}(stat.)^{+1.19}_{-0.80}(syst.) \pm \mathbf{0.29}(\mathbf{theory\ syst}.)$$

$$\hat{\mu}^{\tau\tau}_{\mathbf{VBF+VH}} = 1.24^{+0.48}_{-0.45}(stat.)^{+0.31}_{-0.28}(syst.) \pm \mathbf{0.08}(\mathbf{theory\ syst}.)$$

- Evidence for VBF production at 4.3σ (combining the different decay channels)

$\mu^{WW^*}_{\text{ggF}}$	$1.15^{+0.28}_{-0.24}$		
Ratio of cross sections	Best-fit value	Significance (σ)	
		Observed	Expected
$R_{\text{VBF/ggF}}$	$1.00^{+0.46}_{-0.34}$	4.3	3.8
$R_{VH/\text{ggF}}$	$1.33^{+0.94}_{-0.68}$	2.6	3.1
$R_{ttH/\text{ggF}}$	$1.90^{+1.12}_{-0.86}$	2.4	1.5

ATLAS-CONF-2015-007

Ratio of production cross section over ggF->H->WW (largest rate after event selection)

VH Monte Carlo predictions

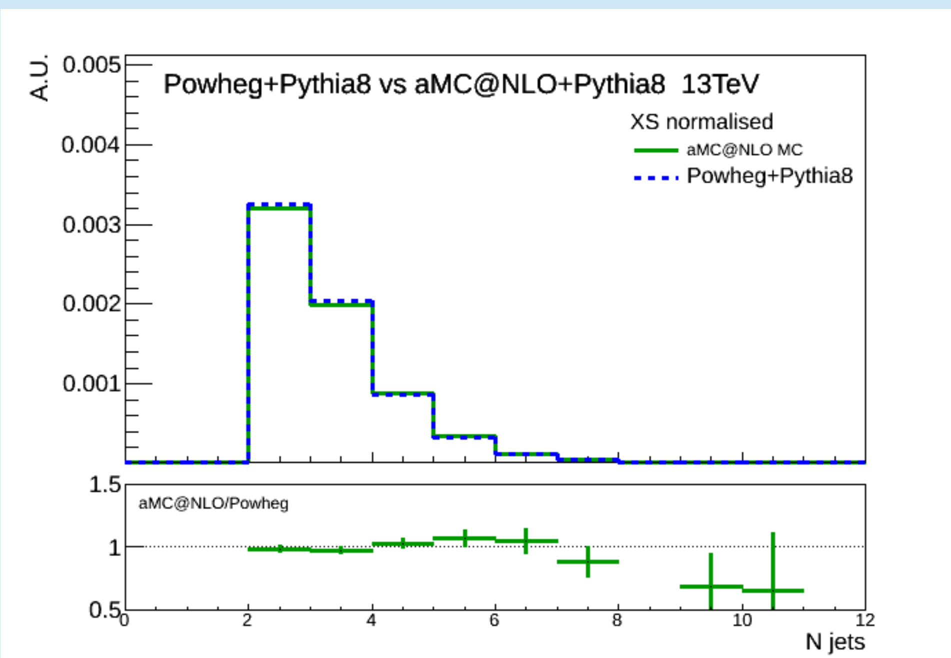
[VH Associated Production] **Powheg + Pythia8**

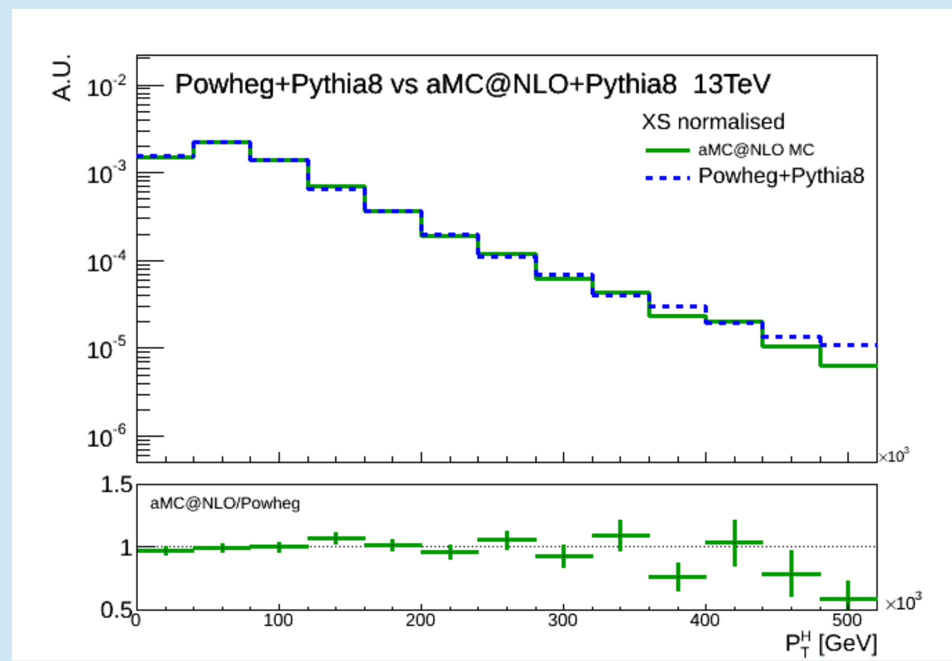
- **WH** and **qq→ZH** (**MiNLO**), all V decay modes available
- **gg→ZH** (are Z hadronic decays available?)
- **ME+PS matching scheme**: vetoed power showers via the **main31** algorithm
- No resummation damping in Powheg (hdamp=+inf)

First validation comparing Powheg+Pythia8 vs aMC@NLO+Pythia8:

- only **WH** and **qq→ZH** available (gg→ZH recently in aMC@NLO)
- **ME+PS matching scheme**: wimpy showers with global recoil scheme

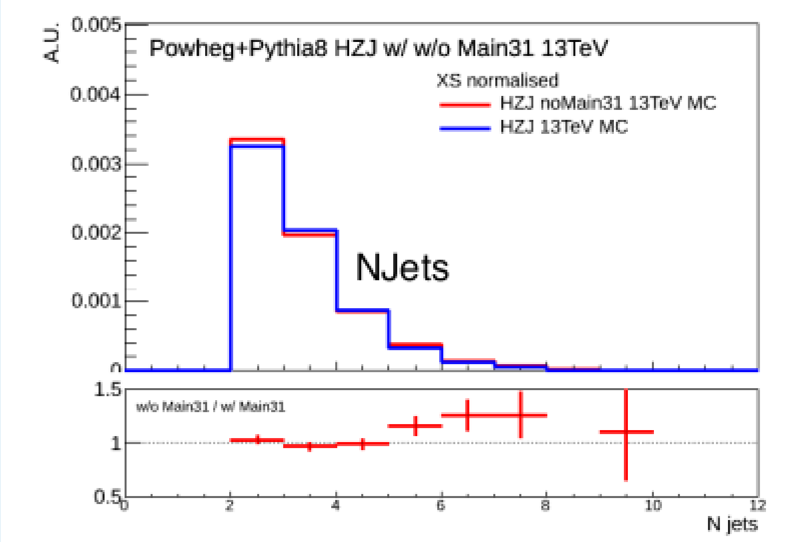
[qq→ZH→eebb] Particle level comparison at 13 TeV: good agreement !

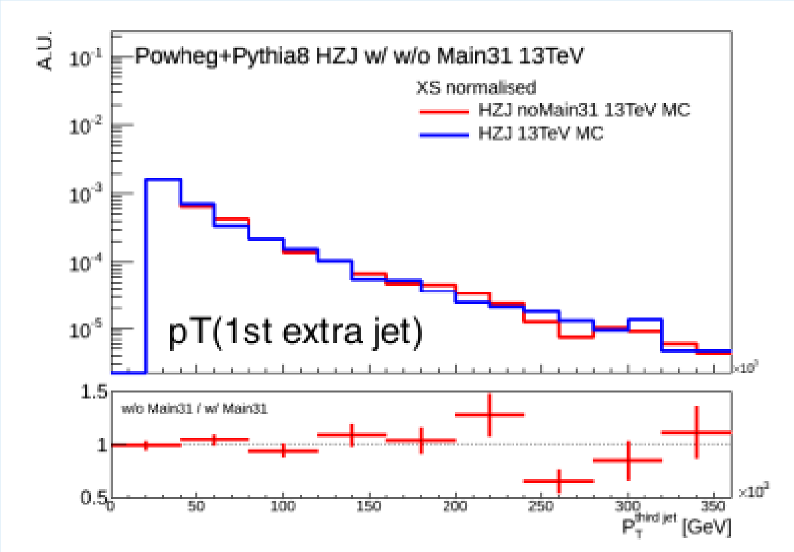




VH Monte Carlo: Powheg+Pythia8

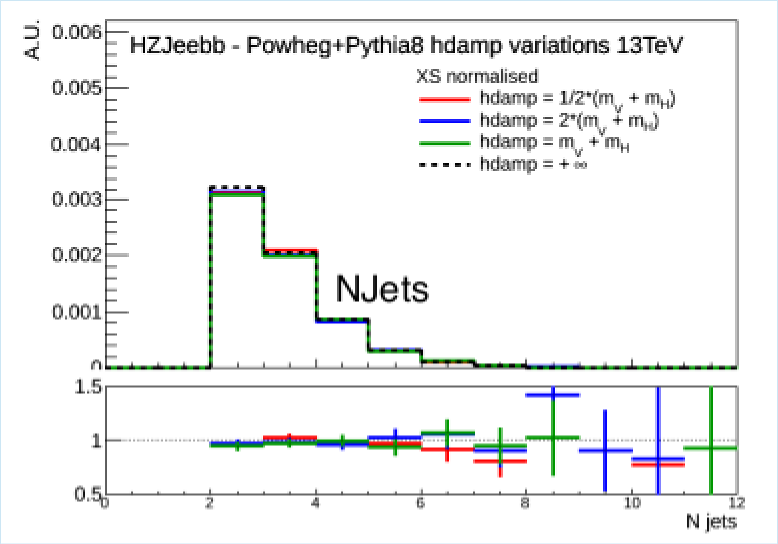
Several studies performed to check the impact of the **ME+PS matching** in **Powheg + Pythia8**
AMain31 matching scheme (vetoed power showers):

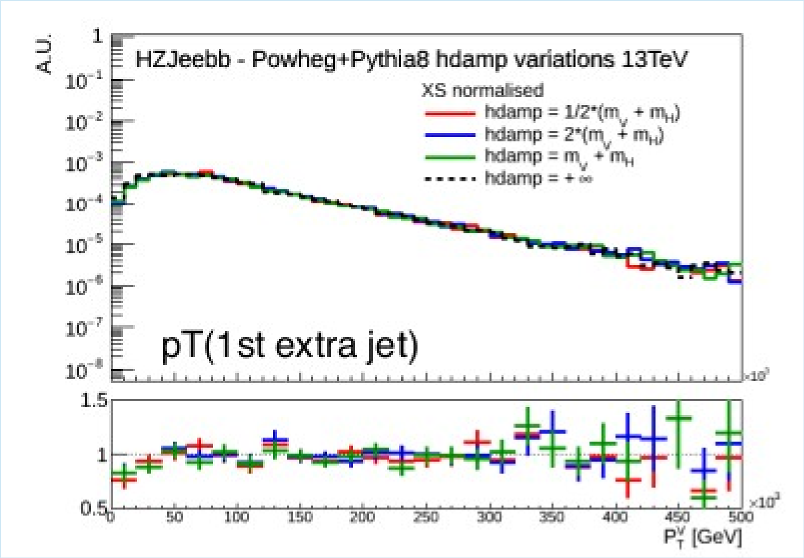




W/o main31
With main31

AThe resummation damping scale in Powheg has been tested: (very small effects on the Z boson distribution, we may check variables for the VH-system: for now hdamp=+inf - open to suggestions - **)**





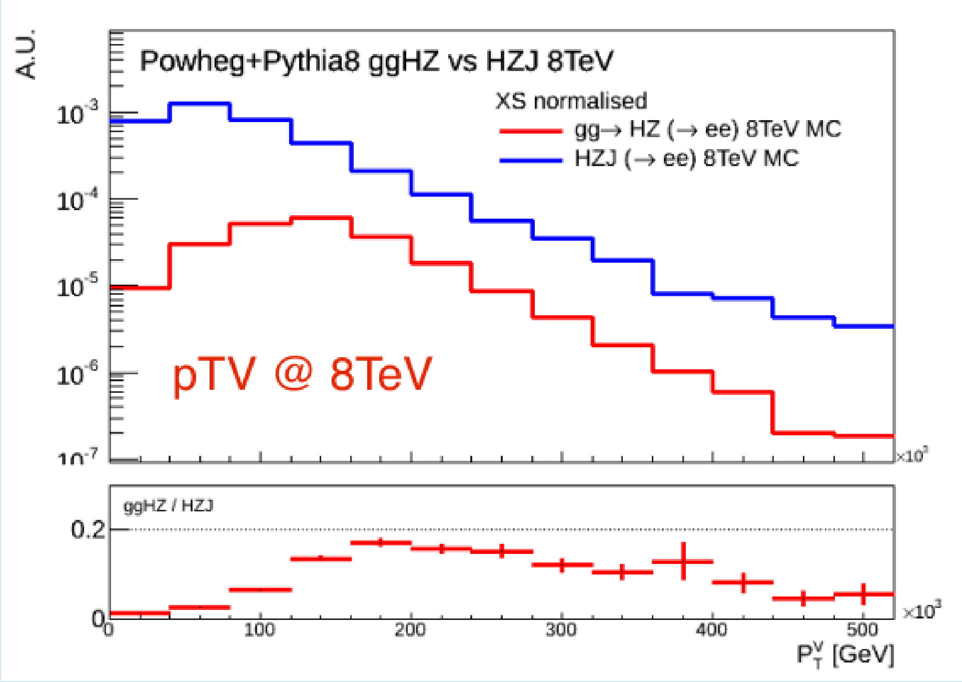
Hdamp variations
- m(VH)
- m(VH)/2
- 2*m(VH)

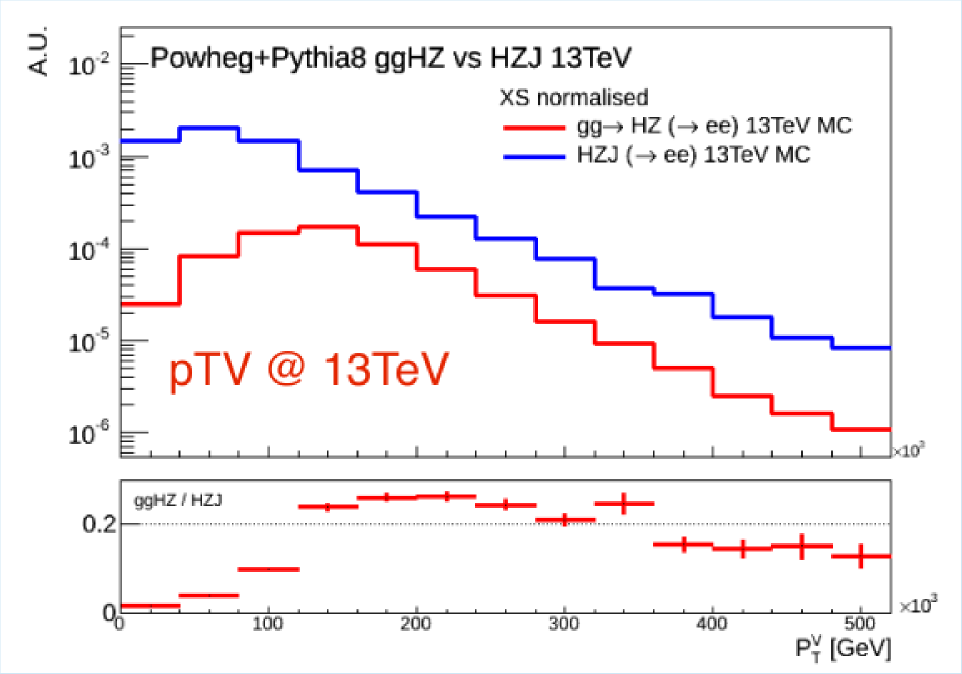
gg→ZH impact @ 13TeV

The **gg-initiated ZH processes** start to contribute at O(alphaS^2) [Powheg provides the LO]

- (8→13TeV) qqZH increases by ~ **2**, while ggZH increases by ~ **3.8**
- gg/qq(ZH) fraction with pTZ>150GeV increases by 70%
- Much larger scale uncertainties than qqZH (~50% in Run1 analysis)

ZH(ee,bbar) channel: qq and gg contributions normalized to their Powheg cross section





NLO correction for gg→ZH are available only for the inclusive cross section in the large mt limit:
K(NLO/LO) ~ 2 (**not applied** in the plots above)

NOTE: until recently gg→ZH was available in Powheg only. Now it's provided by aMC@NLO as well, so a validation of the Powheg prediction is under way.

VH fixed order calculation: hv@nnlo

Several tools available for f.o. calculations: MCFM, VBFNLO, vh@nnlo, hv@nnlo, ...
Focus on hv@nnlo ⟶ **differential NNLO calculation (including gg → ZH contribution)**

Main motivation: NNLO differential VH Monte Carlo prediction

- ME+PS event generation is available at NLO (QCD)
- VH differential XS known up to NNLO (QCD)

Run1 analysis recipe was to normalize the signal XS to the NNLO inclusive prediction
Possible improvement (in developement): **NNLOPS-reweighting of Powheg-MiNLO**

⟶ Not a trivial procedure: 2-body final state require a 5-dim reweighting

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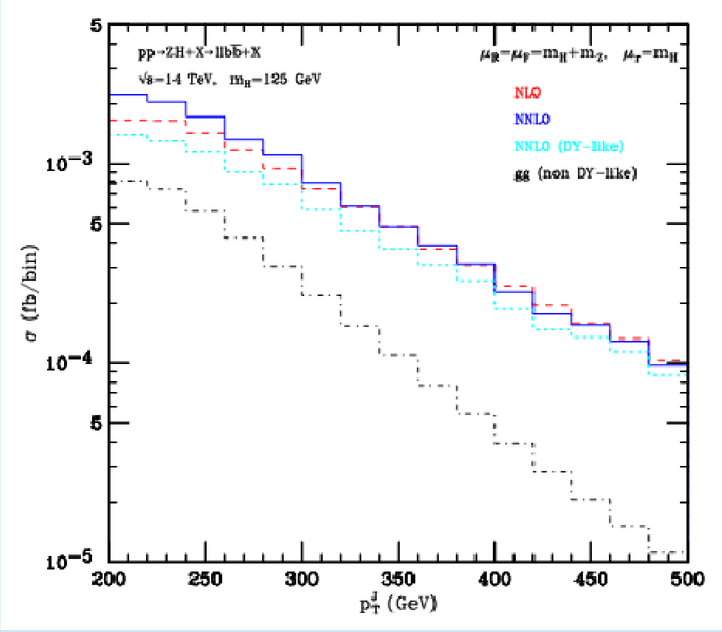
From the hv@nnlo paper: http://arxiv.org/pdf/1407.4747v1.pdf (impact of NNLO prediction)



Boosted analysis selection (pTZ>160GeV, pT(bb)>200GeV)
ZH(ee,bbar) final state:

NNLO = **qqZH** (Drell-Yan) + **ggZH** (non Drell-Yan)

- NNLO Drell-Yan corrections reduce the NLO contribution by ~20%
- NNLO non Drell-Yan (ggZH) contributions of order ~25%, partially compensate the DY XS decrease

VH fixed order calculation: hv@nnlo

The f.o. **NLO calculation** can be compared to the Monte Carlo ME+PS prediction (in our case Powheg MiNLO + Pythia8)

qq → ZH (ee,bbar) final state: cross-section comparison **without any selection**

- **hv@nnlo XS@NLO** = **14.894** (+/- 0.011) fb
- **Powheg XS@NLO** = 25.92 fb * BR(H → bbar) = **14.98** fb

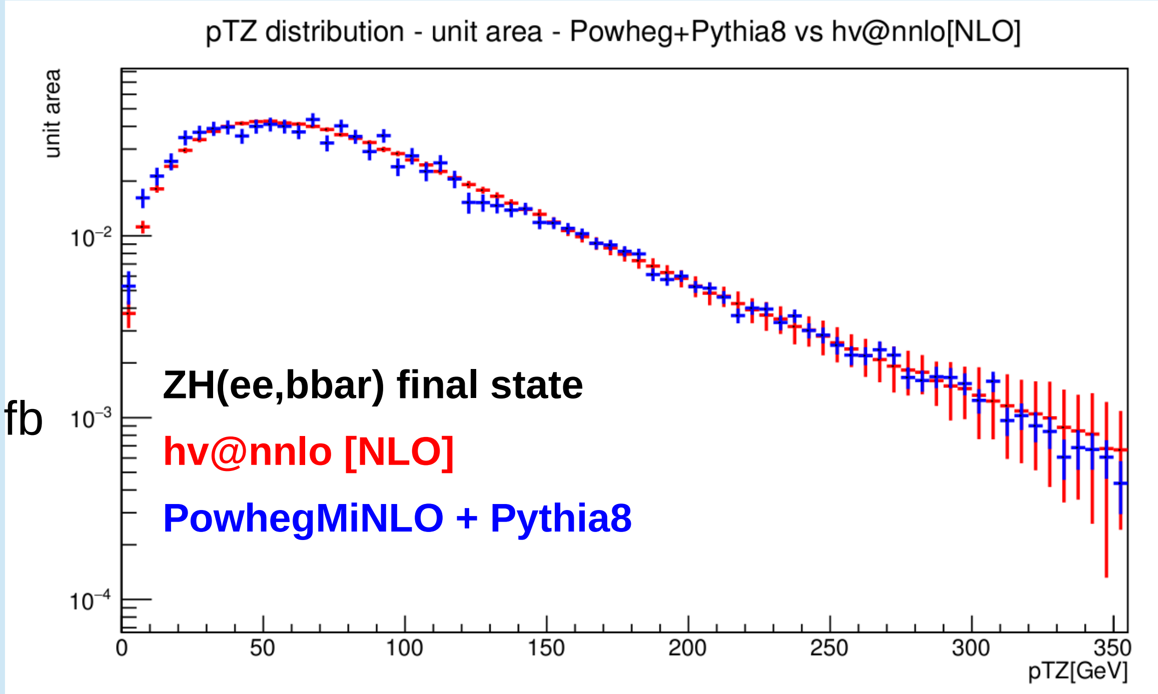
qq → ZH (ee,bbar) final state: simplified SM VHbbar analysis selection applied as consistently as possible to Powheg+Pythia8 and hv@nnlo

- pT(electrons) > 7GeV
- |eta(electrons)| < 2.5

- pT(b-jets) > 20GeV
- |eta(b-jets)| < 2.5

Cross-Section comparison **w/ selection**

- **hv@nnlo XS@NLO = 7.934** (+/-0.007) fb
- **Powheg XS@NLO** = **6.67** fb



Statistics of Powheg samples if quite low (100k evts before cuts) but the shape distribution indicates a good agreement.

Next steps:

- Understand small XS difference
- Check additional variables
- **Already started to include the NNLO calculation (qqZH and ggZH)**

VH theory systematics and corrections

Main systematic uncertainties for VH production mode (from Run1 experience):

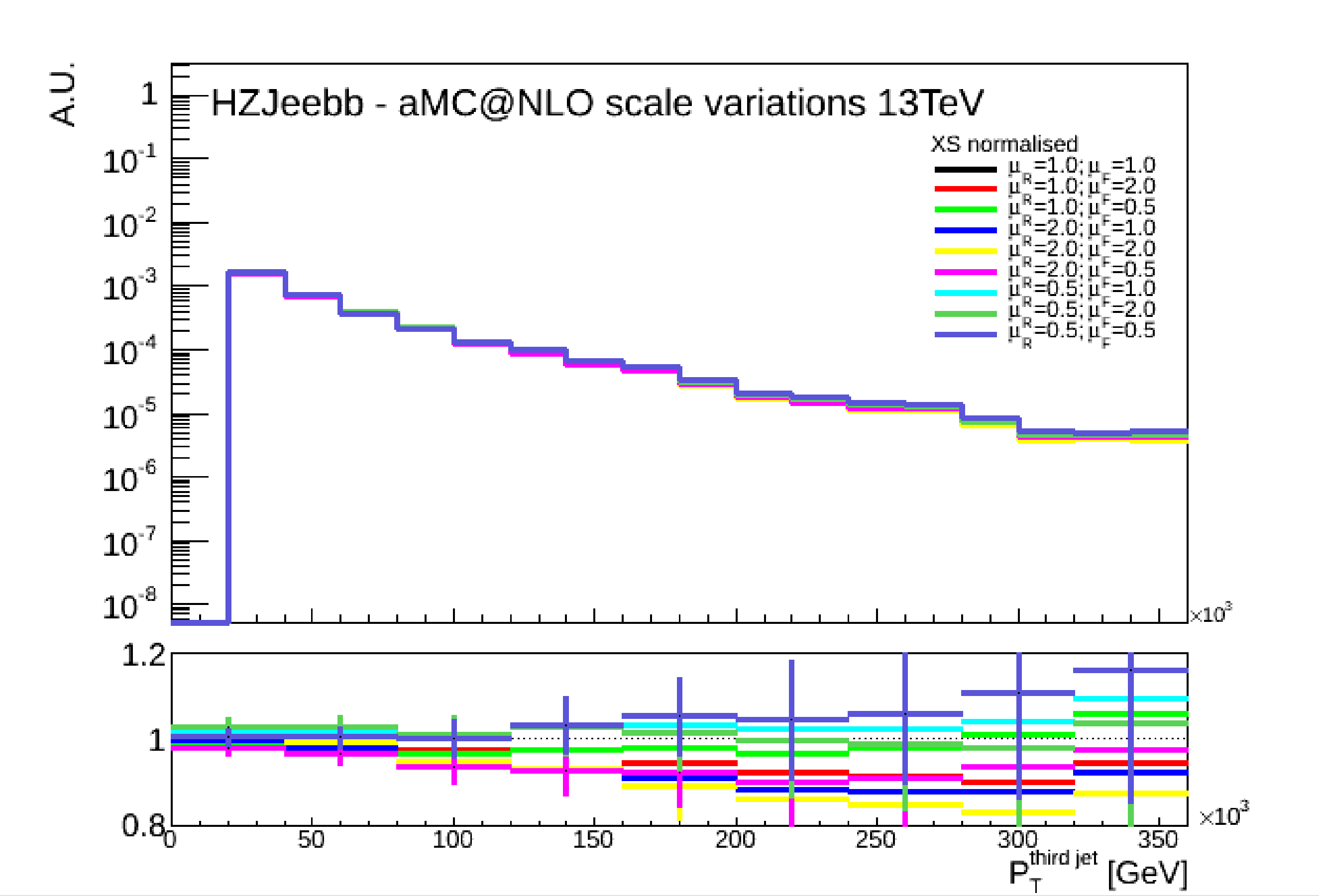
- **Missing higher order corrections** (via scale variations): for the short term we could follow the same prescription as in Run1 (envelope of scale variations + shape uncertainties wrt pTV). For the NNLOPS prediction, how to properly assess these uncertainties?
- **PS / hadronization / UE / MPI**: in Run1 estimated as "2-point" variation by comparing different models (i.e. Powheg+Pythia8 vs Powheg+Herwig).
  Do we have a better defined method to assess this uncertainties?
  Some discussions ongoing from Les Houches
  https://phystev.cnrs.fr/wiki/2015:groups:tools:showeruncertainties
- **Matching uncertainty**: not applied for VH during Run1.
  We are now using a more refined matching scheme (Pythia8 main31 for vetoed showers). Could we assess this systematic within the main31 scheme (by varying the matching parameters) instead that relying on an other "2-point" comparison (e.g. Powheg+Pythia8 vs aMC@NLO+Pythia8) ?
- **PDF uncertainties**: still using the "old" generation of PDF (CT10 for Powheg+Pythia8), we will follow the PDF4LHC prescription

Electroweak corrections:
MC event generator provides NLO(QCD) + NLO(EW) corrections?
Alternative options is to derive differential EW corrections f(pTV) using **HAWK**.

VH theory systematics and corrections

First tests are ongoing to use the **LHEv3 weights functionality** (scales and PDF variations can be obtained via reweighting – weights produced at LHE file level).
Very useful functionality to avoid re-generating samples for all systematic variations!

One test example from aMC@NLO+Pythia8 (ZH→eebbar) for scale variations



Technical point: we noticed that Powheg is able to store the weights in the LHE file, however the LHE file is labelled by default as version "1.0", which causes issues in the propagation of the weights to the HepMC format (it should be "3.0")

VBF Monte Carlo prediction

VBF modelling mainly based on Run1 experience:

- VBF signal modelling is provided by **Powheg+Pythia8** at NLO(QCD)
- EW NLO corrections are provided by HAWK as a function of pTH

EW corrections: interest in having **NLO QCD + NLO EW + PS** all together

(a) Interface tools with NLO EW to PS: HAWK / VBFNLO + PS ?

(b) EW corrections in NLO MC generators: aMC@NLO / Powheg ?

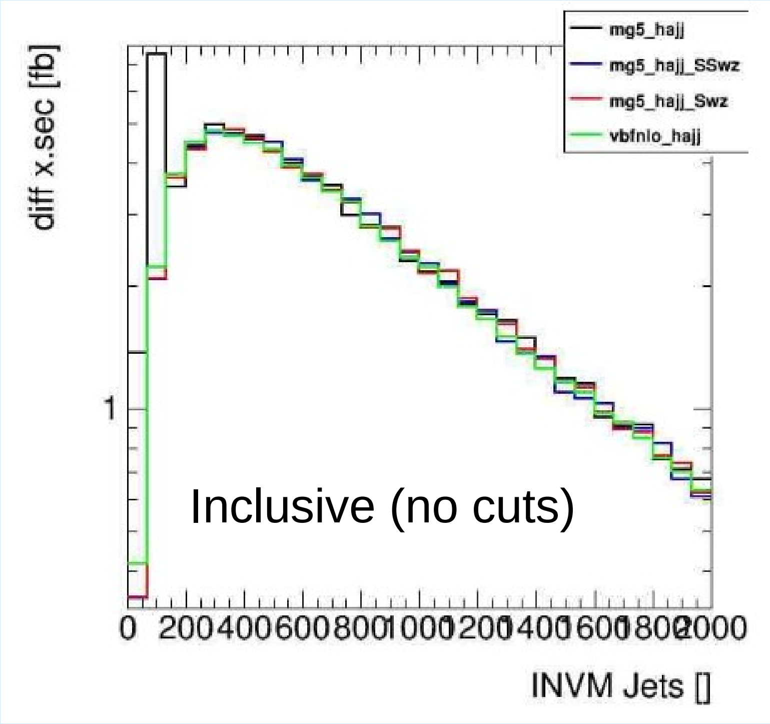
Jet Veto Efficiency and 3rd jet modelling: applying a central jet veto is a key point for VBF experimental analyses, hence control over the 3rd jet modelling is very important

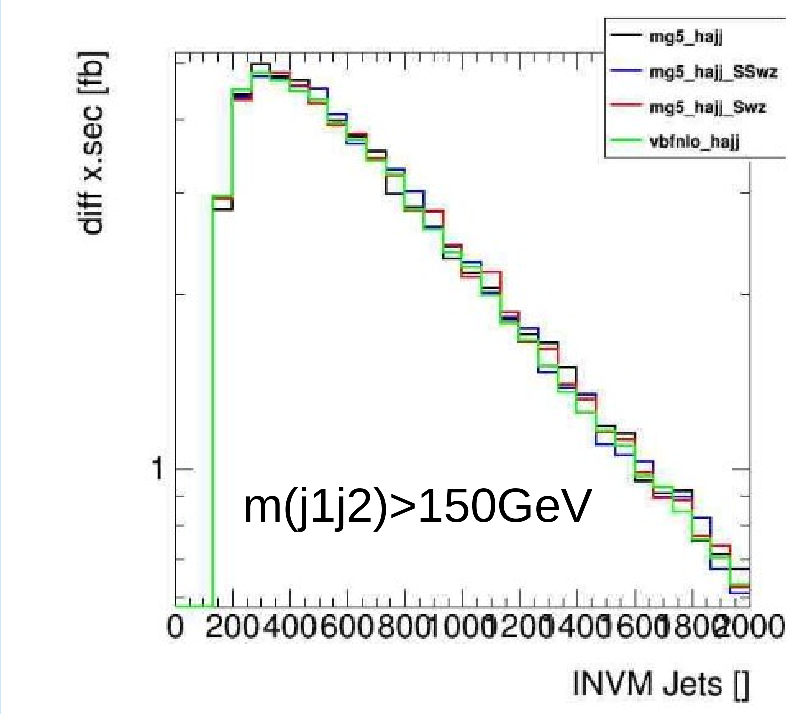
- Both Powheg and aMC@NLO provide NLO (QCD) prediction (3rd jet modeled at ME-level)
- Is NLO+1jet merging available? Could this be obtained via FxFx merging with aMC@NLO?

VBF+γ Monte Carlo prediction

[VBF+γ] First studies are ongoing to validate the MC predictions

- **LO and NLO** cross-section comparison using **aMC@NLO vs VBF@NLO**
  ~5% difference for k(NLO/LO) between aMC@NLO vs VBF@NLO





Parton-level comparison
mg5_hajj
mg5_hajj $$wz
mg5_hajj $wz
vbfnlo_hajj

- **LO vs NLO** aMC@NLO+Pythia8 comparison of **showered events**
  Reasonable results, limited by low statistics

Process of interest for Run2 analysis: validation of MC tools ongoing

VBF theory systematics and corrections

VBF Higgs production has small theory uncertainty in itself (see Run1 **H→ττ** example)

Run1 experience from the H→ττ analysis:

- **UE / PS / hadronization / MPI effects**: encoded in Powheg+Pythia8 vs Powheg+Herwig comparison, leading to 5-10% on signal yield
- **ME+PS matching**: Powheg+Herwig vs aMC@NLO +Herwig leading to 5% effect on signal yield
- **Missing higher orders** (scale variations): range of 1.4-2%
- **EW corrections**: differential modelling of the truth pTH spectrum from HAWK + associated uncertainty
- **PDFs**: following PDF4LHC prescription give a 2-3% yield variation + shape effect up to 5% in the tail of the dijet distribution

Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	$^{+0.27}_{-0.26}$
Jet energy scale	$\pm$ 0.16
Tau energy scale	$\pm$ 0.07
Tau identification	$\pm$ 0.06
Background normalisation	$\pm$ 0.12
Background estimate stat.	$\pm$ 0.10
BR ($H \to \tau\tau$)	$\pm$ 0.08
Parton shower/Underlying event	$\pm$ 0.04
PDF	$\pm$ 0.03

(BR uncertainty not negligible for **H→ττ**)

Main message: Dominant systematic uncertainties are [UE / PS / hadronization and MPI effects] and [ME+PS matching]

Both estimated through “2-point” comparison of different generators.

ggF contamination in VBF-regions

Gluon-fusion induced H+jets production is an important background for VBF signal resgions

Some examples from ATLAS analyses: **ggF contamination (%)**

- $H \rightarrow \gamma\gamma$: VBF-tight(loose) = **20**%(**40**%)
- $H \rightarrow WW$: **30**%
- $H \rightarrow \tau\tau$(lep-had) : **35-43**% [10-15% from the last BDT bin]

MC tools for H+2jets modelling are under study (in parallel with ggF WG1 subgroup):

- HJ, HJJ from Powheg+MiNLO
- MEPS@NLO
- aMC@NLO merged with FxFx procedure
- New GoSAM ggH HJJJ included in Sherpa for ME+PS (in developement)

During Run1 we relied on **Powheg (H inclusive) NLO+PS prediction**, reweighting the Powheg pTH spectrum of the 2-jet bin to match the HJJ Powheg+MiNLO prediction.
This means that the >= 2-jet region relies on the **parton shower modelling** of extra radiation.

New tools are under study to get a more accurate modelling of this (important) background for VBF-like final states.

VBF reweighting tools

VBF production mode could be an interesting tool to probe BSM physics signature, e.g. CP-violation for the Higgs sector.

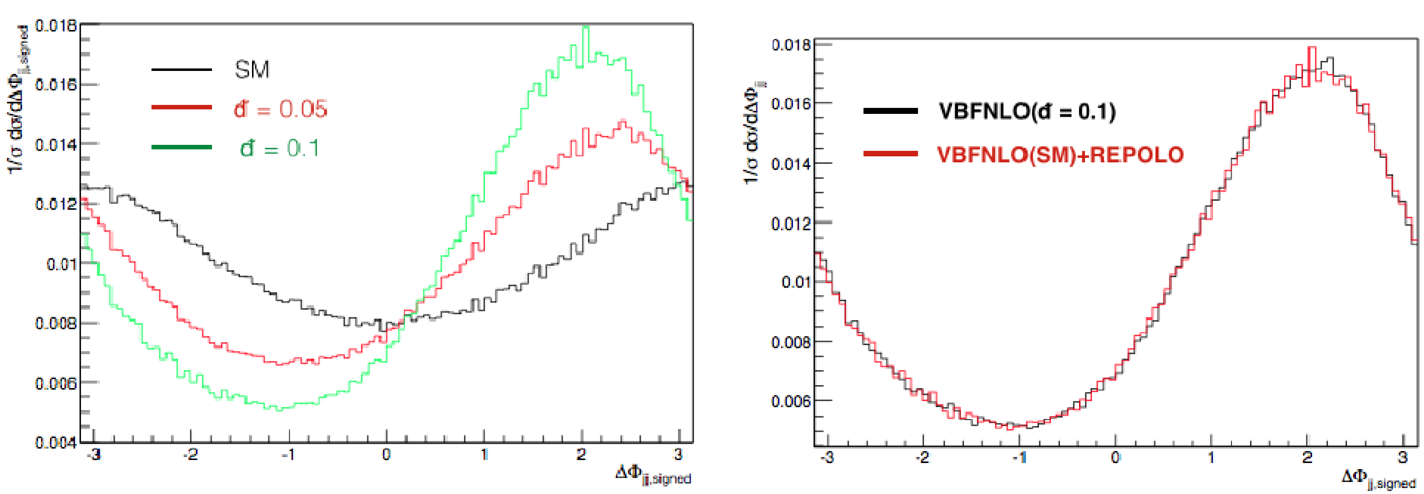
Generating full detector simulation samples for different scenarios is very expensive:

- Powheg provides the “nominal” SM VBF prediction
- aMC@NLO provides benchmark scenarios for CP-even/CP-odd mixing
- **REPOLO** tool used to reweight Powheg prediction / validated vs aMC@NLO
  REPOLO is a **LO ME reweighting tool** - still under validation

$$\frac{|\mathcal{M}_{\mathrm{BSM}}|^2}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

- First studies reweighting Powheg prediction to **HAWK matrix-element**
  HAWK can provide ME at LO for (2->2+H) and (2->3+H) processes, giving a good approximation of the full NLO reweighting

REPOLO Validation (w/ VBFNLO or POWHEG): $\tilde{d} \rightarrow$ additional CP-odd HVV-couplings for SM Lagrangian



SM vs 2 mixture scenarios in VBFNLO

REPOLO validation

VH / VBF Conclusion and Whishlist

Several MC tools have been (and are) studied for VH / VBF production, with many open points still remaining for discussion:

Common points:

- **Systematic uncertainties**: dominant systematics [**PS / matching**] estimated comparing different models (“2-point” systematic) --> A final prescription may be far away to come, but could we do better?
- **Electroweak correction**: ME+PS (NLO QCD + NLO EW) ?
- **Reweighting tools** to explore BSM scenarios: under study (especially for VBF)

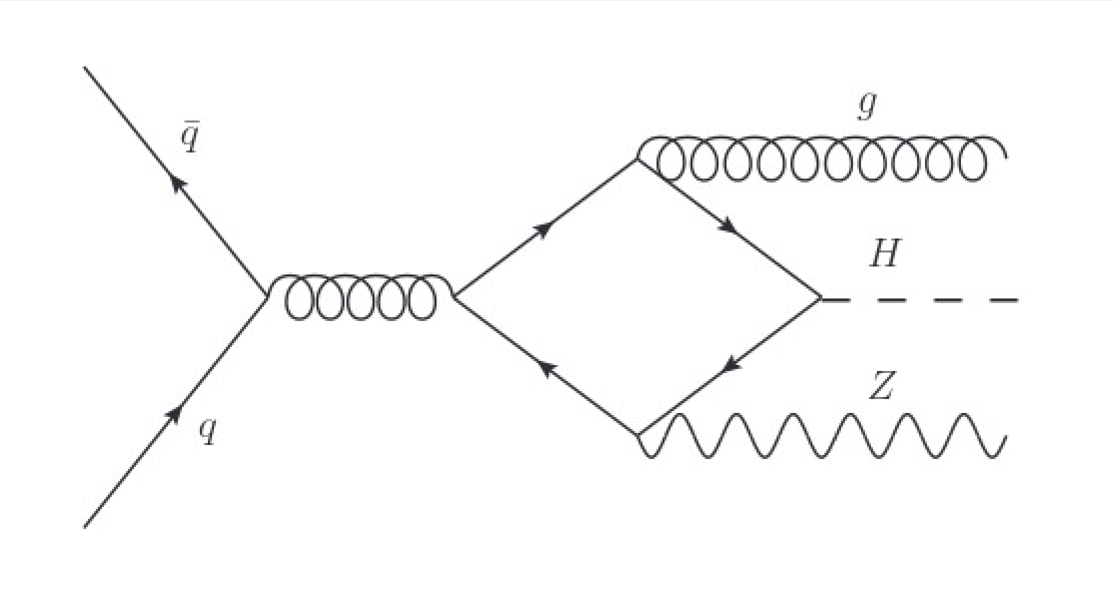
VBF vector boson fusion:

- First preliminary studies for **VBF+γ** : interesting channel for Run2 analysis
- Open points regarding higher order predictions for an accurate modelling of the extra radiation (to be vetoed in the analyses)
- Reweighting strategies: **REPOLO** and **HAWK** being tested

VH associated production:

- **Powheg and aMC@NLO MC** prediction have been studied and seem under control (aMC@NLO good candidate to study EFT scenarios)
- **ggZH** contribution (very relevant at 13TeV) relying on very large NLO k-factor
- Fixed order differential prediction at **NNLO QCD** available: are we using this tool at his full potential?

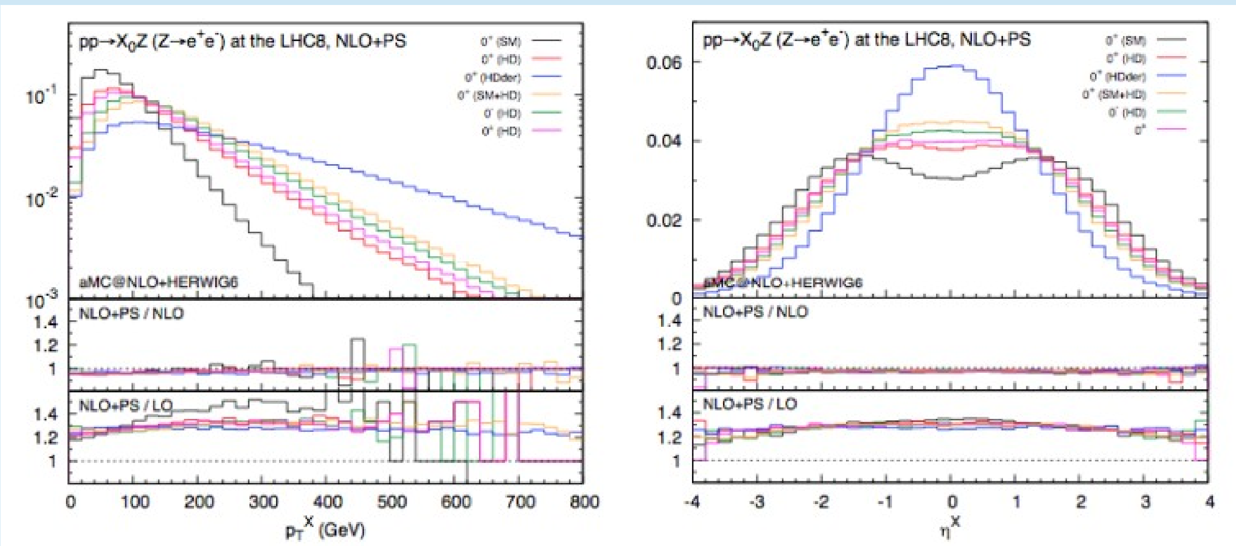
BACK-UP



VH EFT benchmarks with aMC@NLO

The VH→bbar channel is able to constrain some combination of parameters related to the dim-6 operators used to build EFT Lagrangians (related to the HZZ and HWW couplings)
[http://arxiv.org/pdf/1404.3667.pdf; http://arxiv.org/pdf/1406.7320.pdf]

aMC@NLO provides NLO+PS VH predictions within the EFT framework, setting the EFT Lagrangian parameters for different benchmark schemes [http://arxiv.org/pdf/1311.1829.pdf]



$$\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{SM} \Big[\frac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W^+_\mu W^{-\mu}\Big] \\
& - \frac{1}{4}\Big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu}\widetilde{A}^{\mu\nu}\Big] \\
& - \frac{1}{2}\Big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu}\widetilde{A}^{\mu\nu}\Big] \\
& - \frac{1}{4}\Big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\Big] \\
& - \frac{1}{4}\frac{1}{\Lambda}\Big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu}\Big] \\
& - \frac{1}{2}\frac{1}{\Lambda}\Big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu}\widetilde{W}^{-\mu\nu}\Big] \\
& - \frac{1}{\Lambda} c_\alpha \Big[\kappa_{H\partial\gamma}\, A_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} \\
& \qquad + \big(\kappa_{H\partial W} W^+_\nu \partial_\mu W^{-\mu\nu} + h.c.\big)\Big]\Big\} X_0 , \qquad (1)
\end{aligned}$$

First tests generating EFT benchmark VH signals have started (first validation vs aMC@NLO paper successful -many thanks to Marco Zaro for his help-).
Generating several samples with full detector simulation is expensive, so reweighting strategies are under investigation.

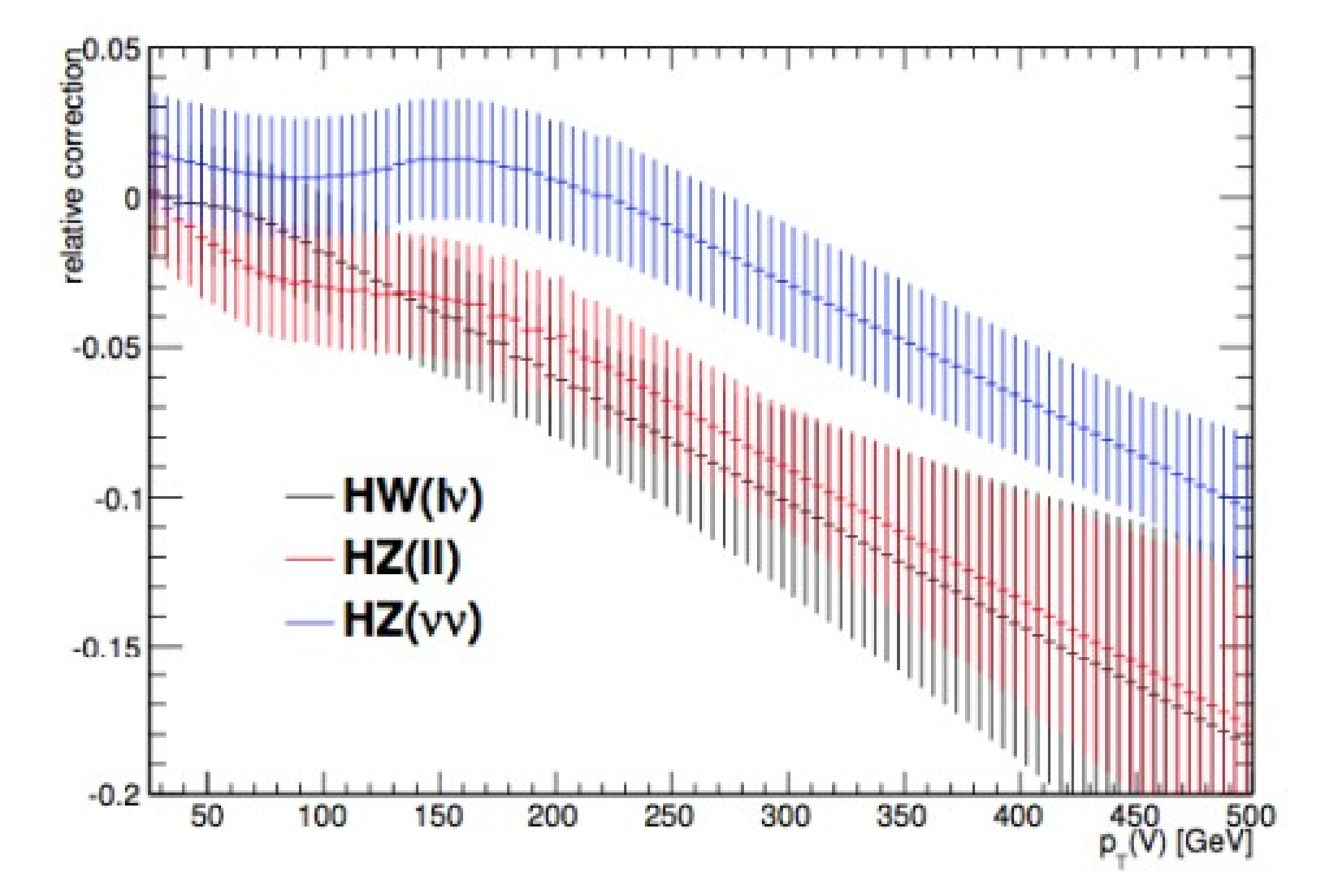
REPOLO: reweighting tool designed to reweight Powheg nominal samples to different parameter configurations [yet to be studied] – LO ME [BSM/SM]

Possible strategy: reweight Powheg nominal samples + validate reweighting vs aMC@NLO EFT benchmarks

Run1 EW corrections

Electroweak corrections:
No MC event generator provides NLO(QCD) + NLO(EW) corrections. The plan is to derive differential EW corrections f(pTV)

https://twiki.cern.ch/twiki/bin/viewauth/AtlasProtected/HiggsCrossSection#VH_cross_section_correction_as_f



VBF reweighting tools: HAWK

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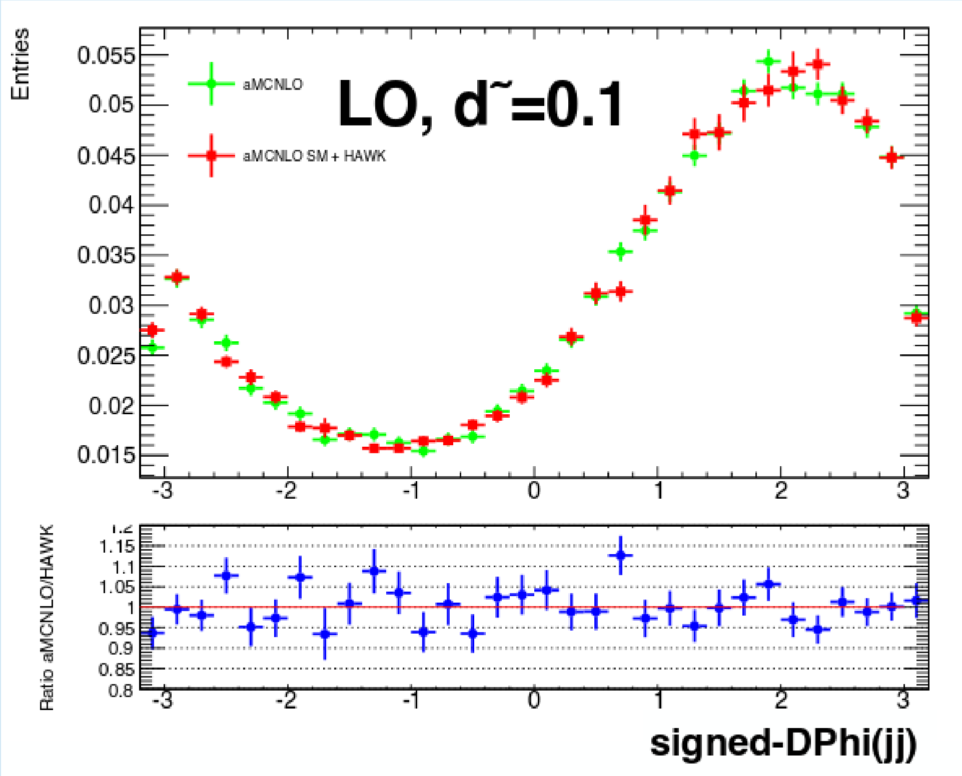

First validation of HAWK reweighting:
- LO process from aMC@NLO
- reweighted to CP-mixed scenario via HAWK matrix element

NLO reweighting validation is ongoing