# Overview of VH WG1 experimental/theory status

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WG1 - VH group meeting - November 8, 2021

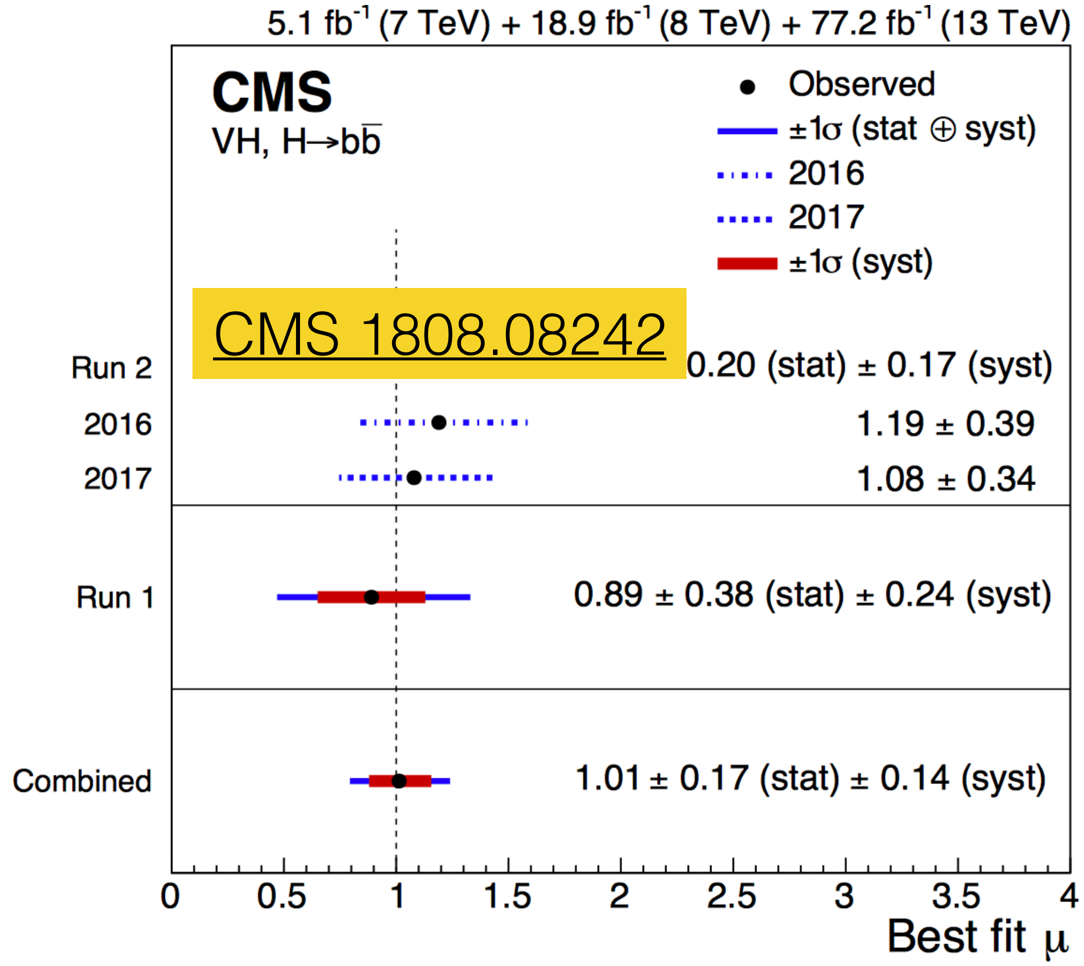
# Outline of the talk

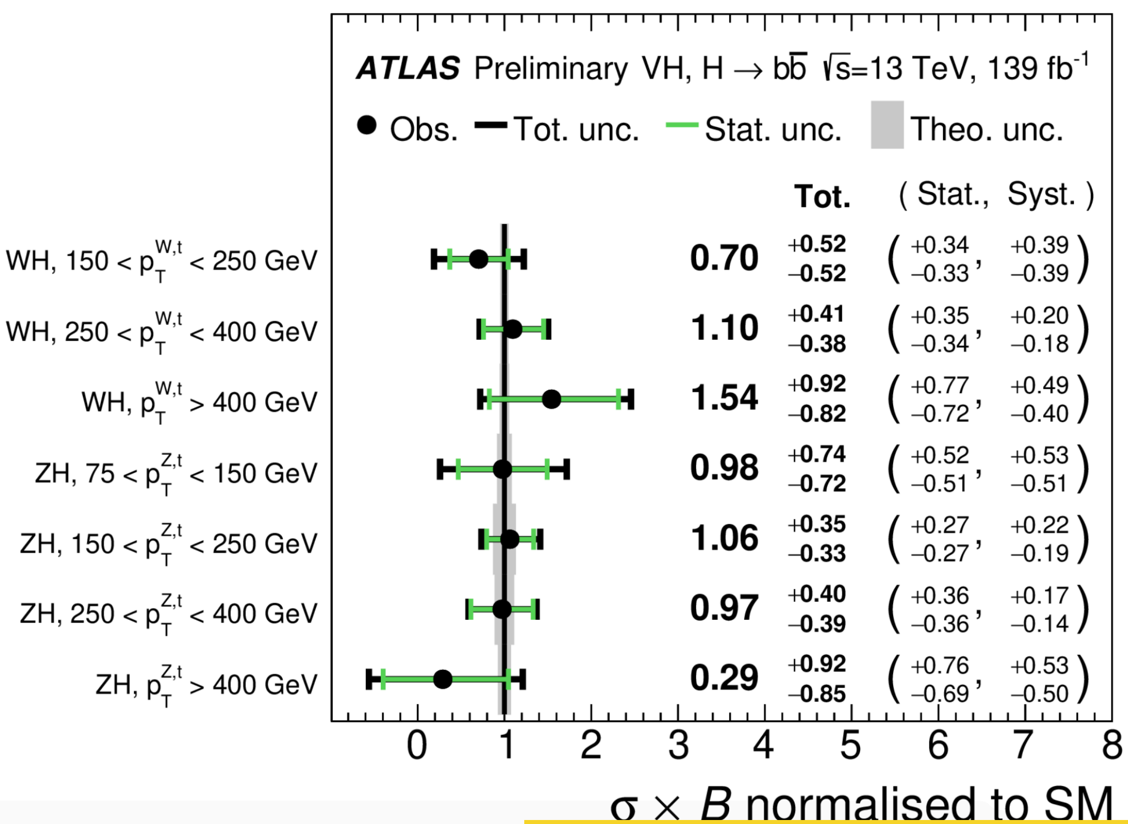


- ➡ LHC Higgs WG1 - VH sub-group [twiki], WG1 fall meeting at this link
- ➡ Quick overview of the state-of-the-art for ATLAS&CMS VHbb measurements
  - new developments wrt last LHC Higgs WG workshop [Nov 2020] marked as NEW
- ➡ VH signal uncertainties - theoretical developments and feedbacks from the analyses
  - signal uncertainties on STXS measurement [backup slides]
  - ggZH merged predictions
  - review of qqZH processes
  - signal modelling of Hbb branching ratio and decay
- ➡ Background uncertainties - theoretical developments and feedbacks from the analyses
  - a quick glance at the non V+X backgrounds
  - V+jets (V+heavy-flavour) modelling - ATLAS/CMS comparisons and state-of-the art of the investigations
- ➡ Wrapping-up and conclusions

# Run 2 VHbb measurements - the state of the art

CMS 1808.08242

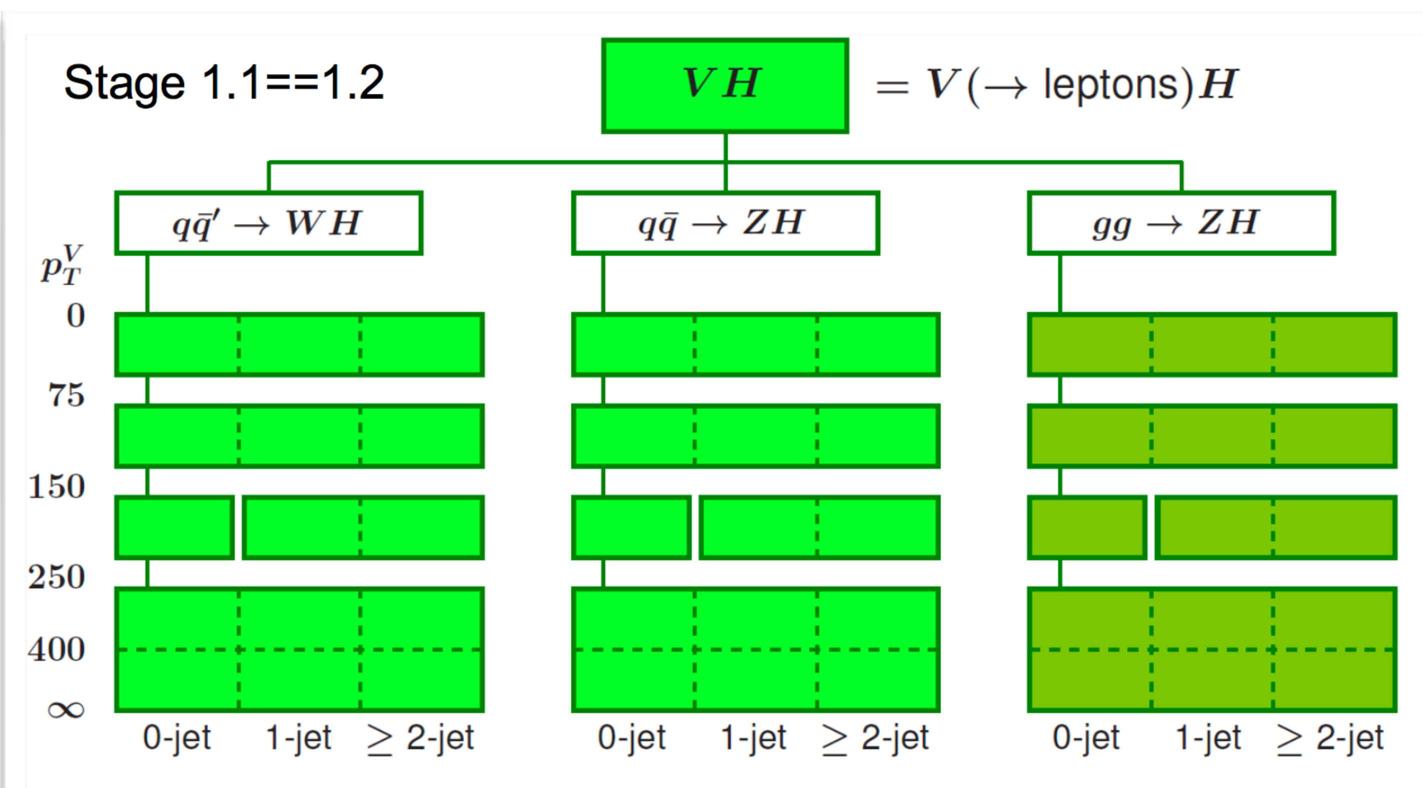



ATLAS-CONF-2021-051

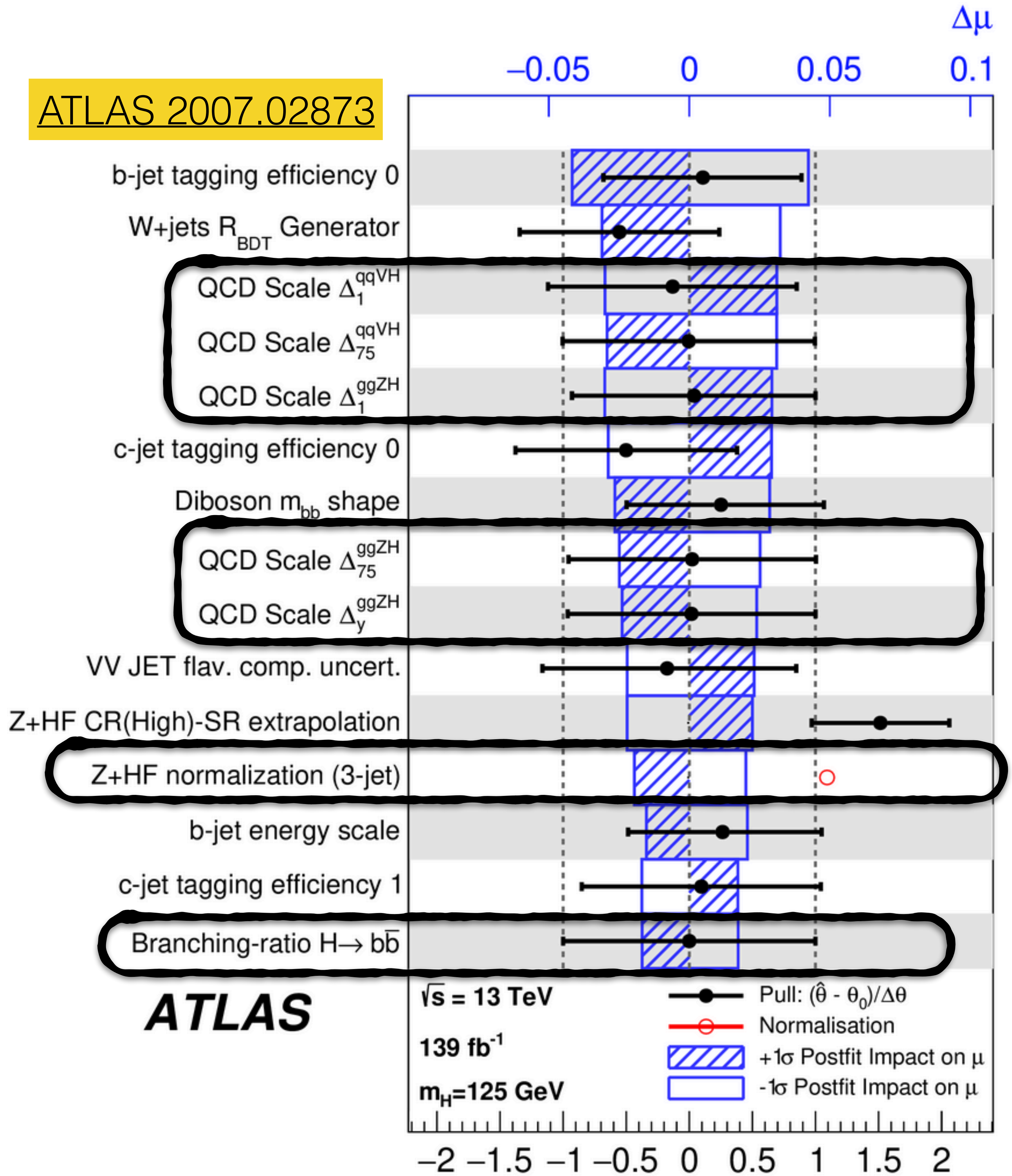
- Evolution of inclusive measurements - STXS approach categorises events at gen-level using analyses observables (ptV, ptH, nJet, …)
- Signal extraction is optimised for kinematic features of specific bin
- Several points of interest for analysis sensitivity (bins to target, what to do with non-sensitive bins, define dedicated bins to be sensitive to NP effects, … )

CERN YR4



# Limitations of the current measurements - the role of the uncertainties

ATLAS 2007.02873




- ➡ Large uncertainties relate to theory modelling
  - VH signal, Hbb decay
  - V+jets (especially V+HF) modeling
- ➡ Will review the status of the investigations for modelling/ predictions as well as the new features currently under study within the VH LHC Higgs sub-group

| Uncertainty source | $\Delta\mu$ | |
|---|---|---|
| Statistical | +0.26 | −0.26 |
| Normalization of backgrounds | +0.12 | −0.12 |
| Experimental | +0.16 | −0.15 |
| b-tagging efficiency and misid | +0.09 | −0.08 |
| V+jets modeling | +0.08 | −0.07 |
| Jet energy scale and resolution | +0.05 | −0.05 |
| Lepton identification | +0.02 | −0.01 |
| Luminosity | +0.03 | −0.03 |
| Other experimental uncertainties | +0.06 | −0.05 |
| MC sample size | +0.12 | −0.12 |
| Theory | +0.11 | −0.09 |
| Background modeling | +0.08 | −0.08 |
| Signal modeling | +0.07 | −0.04 |
| Total | +0.35 | −0.33 |

CMS 1808.08242

ETH zürich

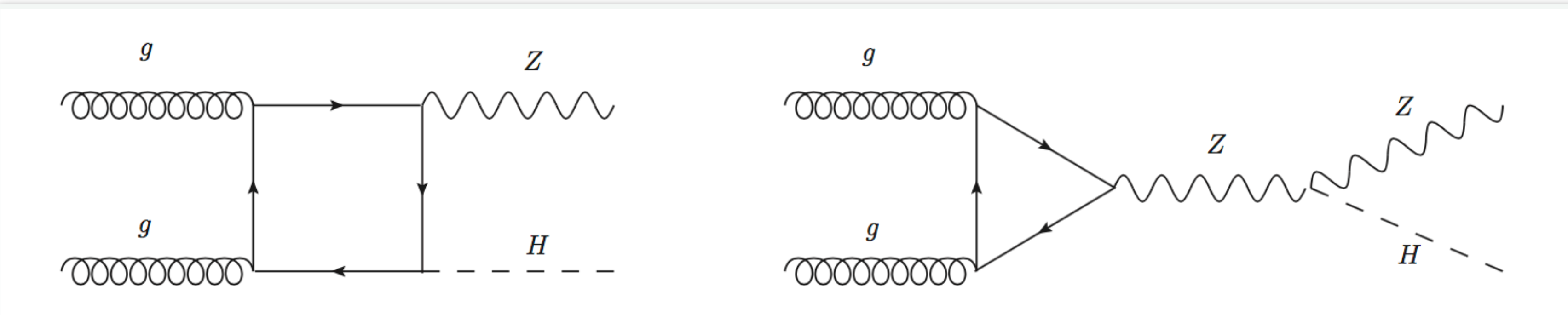
# Signal modeling

# Signal modeling of ggZH process

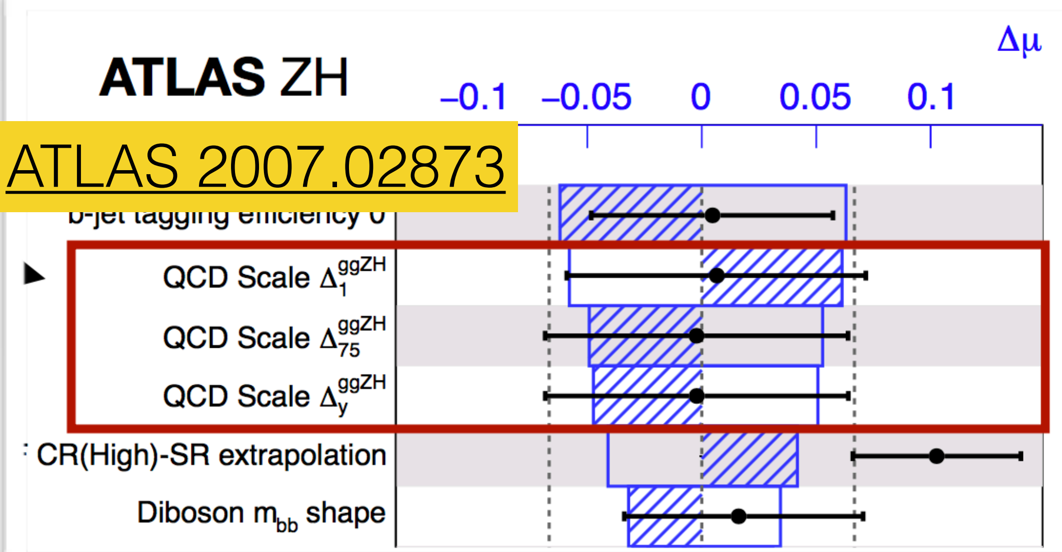
ATLAS 2007.02873

| | Signal |
|---|---|
| Cross-section (scale) | 0.7% ($qq$), 25% ($gg$) |
| $H \to b\bar{b}$ branching fraction | 1.7% |
| Scale variations in STXS bins | 3.0%–3.9% ($qq \to WH$), 6.7%–12% ($qq \to ZH$), 37%–100% ($gg \to ZH$) |
| PS/UE variations in STXS bins | 1%–5% for $qq \to VH$, 5%–20% for $gg \to ZH$ |
| PDF+$\alpha_S$ variations in STXS bins | 1.8%–2.2% ($qq \to WH$), 1.4%–1.7% ($qq \to ZH$), 2.9%–3.3% ($gg \to ZH$) |
| $m_{bb}$ from scale variations | M+S ($qq \to VH$, $gg \to ZH$) |
| $m_{bb}$ from PS/UE variations | M+S |
| $m_{bb}$ from PDF+$\alpha_S$ variations | M+S |
| $p_T^V$ from NLO EW correction | M+S |

**ATLAS & CMS:**
Powheg ggZH@LO in QCD




➡ Scale uncertainties are quite large - full NLO calculation important to mitigate effect associated to scale variations




ATLAS 2007.02873

ggZH uncertainties (QCD scale) largely impactful at pre- and post-fit level

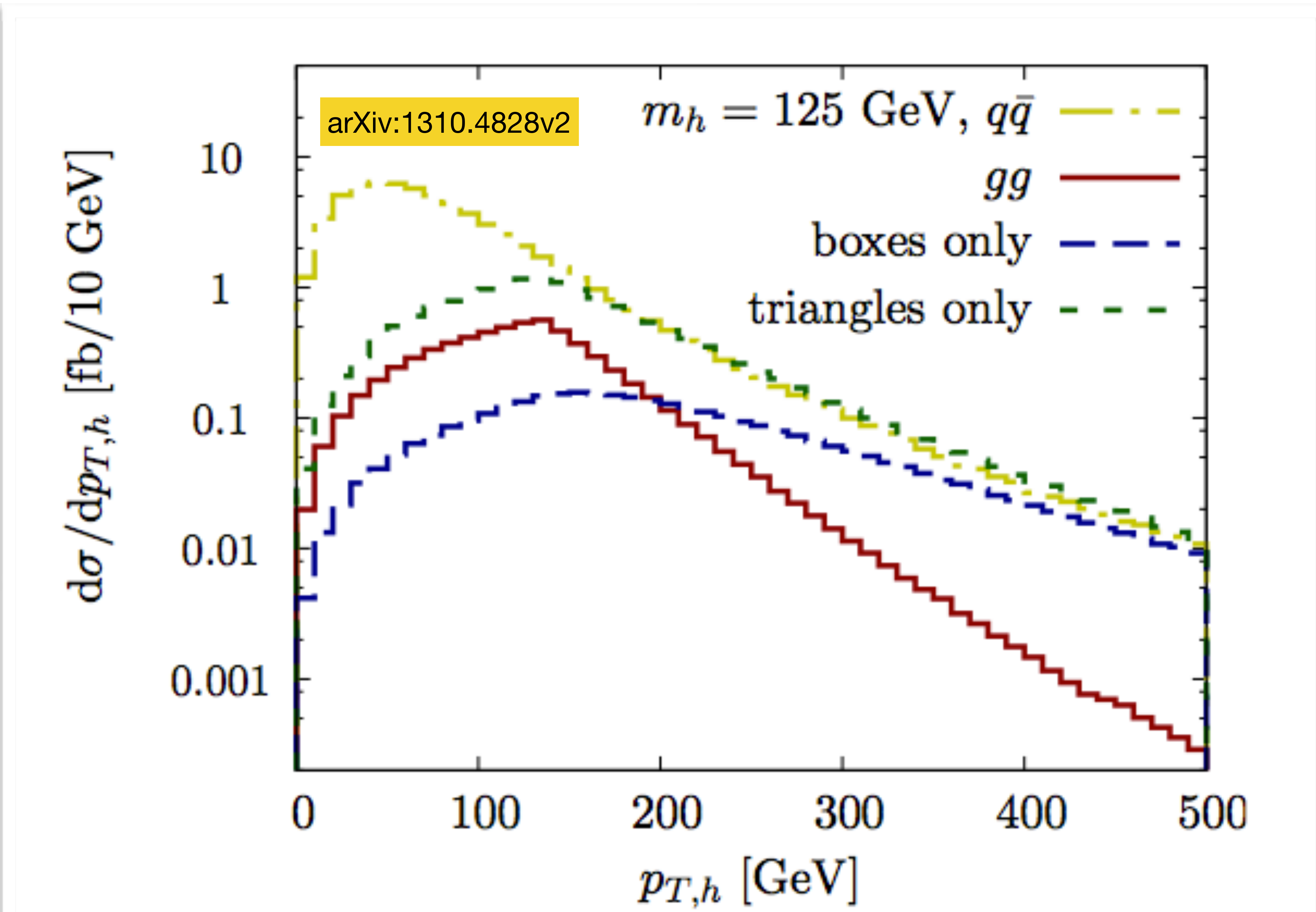
| Process | Cross Section (pb) | +QCD Scale % | -QCD Scale % | ±(PDF+$\alpha_s$) % | ±PDF % | ±$\alpha_s$ % |
|---|---|---|---|---|---|---|
| pp→ZH | 0.8839 | +3.8% | -3.1% | ±1.6% | ±1.3% | ±0.9% |
| qq/qg→ZH, gg→HZ+qqbar (all but gg→ZH) | 0.7612 | +0.5% | -0.6% | ±1.9% | ±1.7% | ±0.9% |
| gg→ZH | 0.1227 | +25.1% | -18.9% | ±2.4% | ±1.8% | ±1.6% |

CERN YR4

# Signal modeling of ggZH process



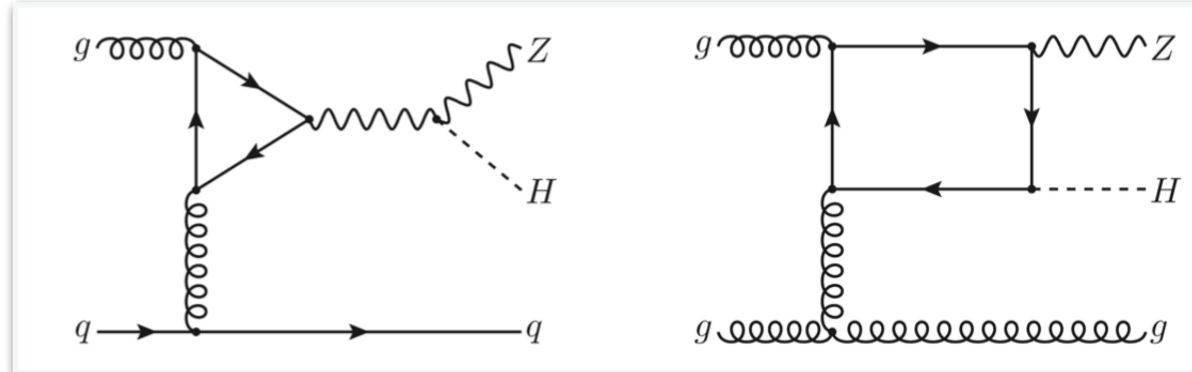
- Important to account for ggZH contribution as part of inclusive ZH signal cross-section
  - XS(ggZH) 15% of inclusive ZH xsec - strong Hpt dependency and enhances contribution in medium VPT range - threshold effect at m(VH)

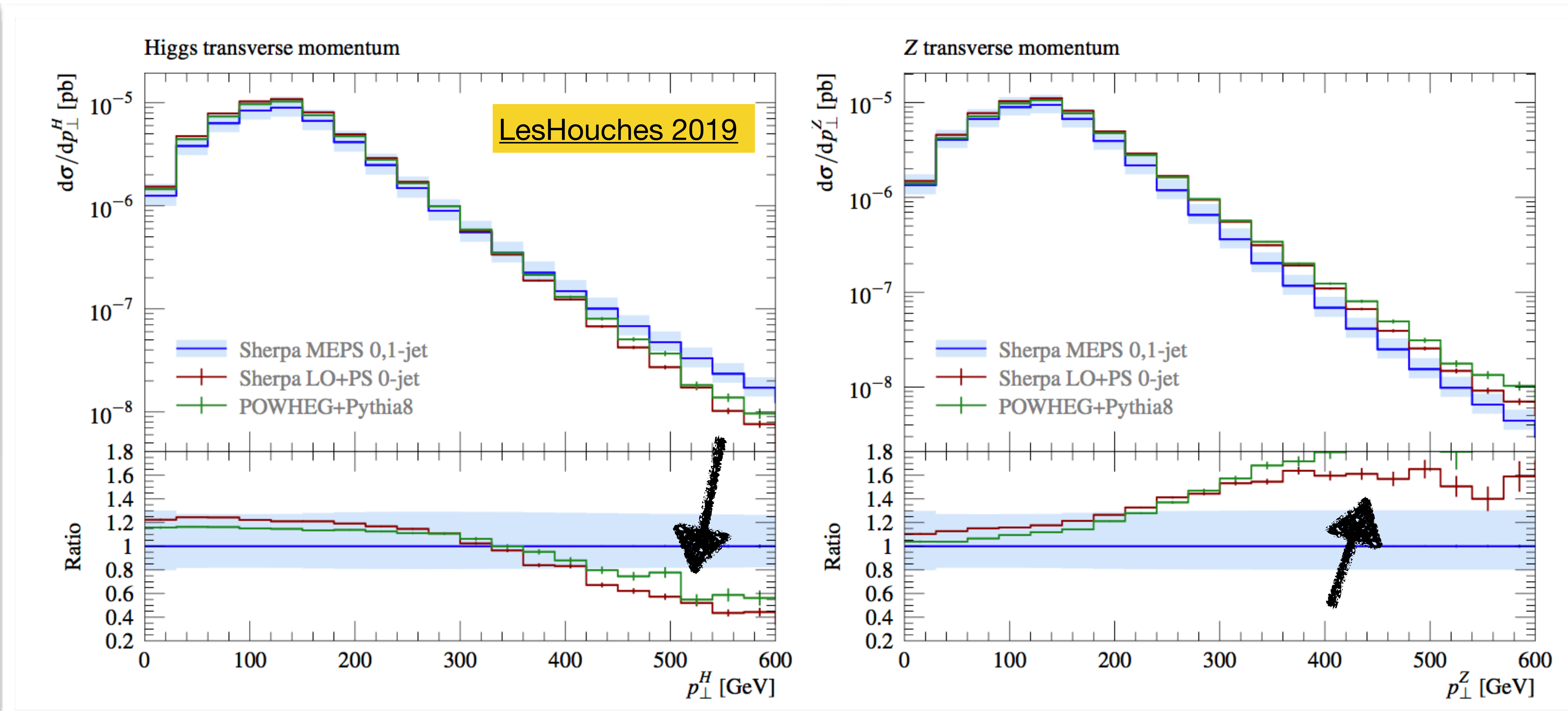


# Signal modeling of ggZH process - hard scattering

➡ Adding 2→3 processes, i.e. gg→ZH+0,1j merged prediction (Sherpa & MC@NLO).

- sizeable modifications in ptH/ptV spectra

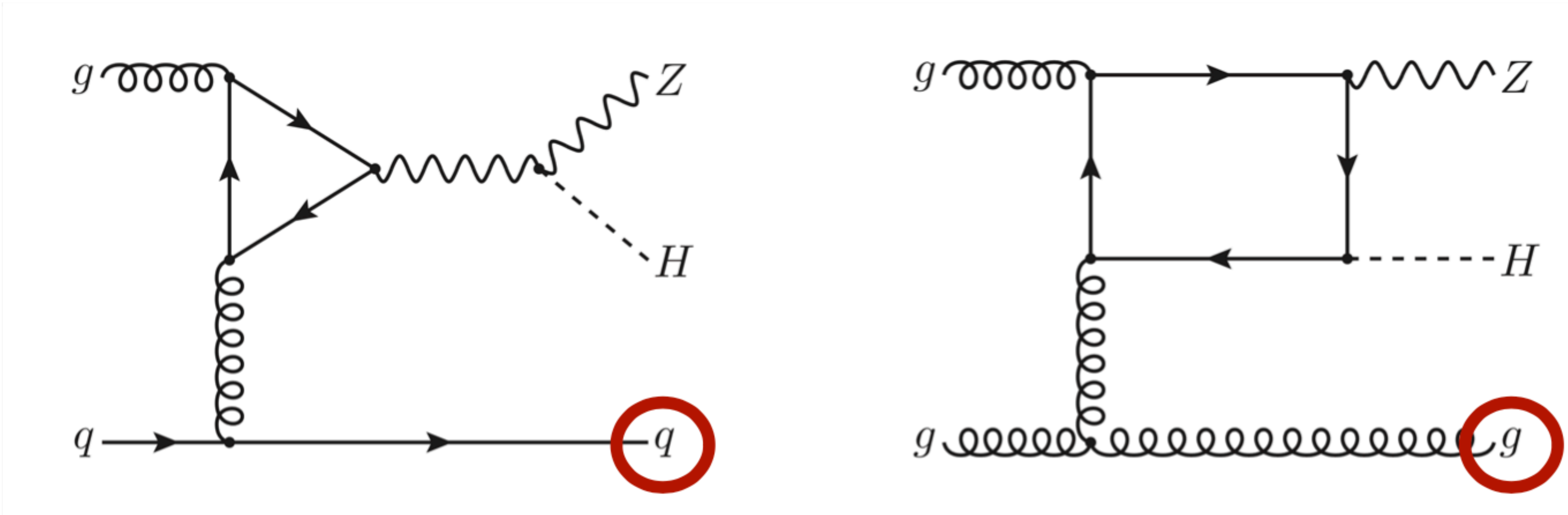



➡ Increase of QCD scale uncertainties in 2→3 processes wrt Powheg+Pythia 2→2 (23% →38% on total ggZH cross-section)

# NEW Signal modeling of ggZH process in ATLAS

➡ Goal: improve modelling of ggZH kinematics: add 2→3 process into matrix element (LO)




➡ Sherpa:

- implemented in ATLAS production environment based on LesHouches setup, performed ATLAS validation
- missing information in truth record, not used for STXS classification paper

➡ MadGraph:

- Developed MadGraph+P8 implementation and full ATLAS validation
- STXS categorisation possible with HXSWG Rivet routine

Ongoing comparison in ATLAS of MadGraph and Sherpa: central values found to be compatible within scale variations but Sherpa assigns larger scale variations than Madgraph (40% vs 25%)

# Signal modeling of qqZH process

ATLAS 2007.02873

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| $m_{bb}$ from PDF+$\alpha_S$ variations | M+S |
| $p_T^V$ from NLO EW correction | M+S |

ATLAS & CMS:
Powheg
qqZH@MiNLO
(QCD)
VPT reweighting
@NLO for EW

- Relatively large variations of ATLAS PS/UE uncertainties originated by two-point systematics difference between Pythia8 and Herwig 7

- Additional predictions available for qqZH modelling:
  - qqVH available for Powheg @NLO QCD+EW
  - ZH @ NNLOPS (reweighting from Powheg to MCFM), WH+jets @ NNLO
  - being tested and included in CMS/ATLAS analyses

CMS 1808.08242

| Uncertainty source | $\Delta\mu$ | |
|---|---|---|
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| Background modeling | +0.08 | −0.08 |
| Signal modeling | +0.07 | −0.04 |
| Total | +0.35 | −0.33 |

# Signal modeling of branching ratios and Hbb decays



ATLAS 2007.02873

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| $m_{bb}$ from PS/UE variations | M+S |
| $m_{bb}$ from PDF+$\alpha_S$ variations | M+S |
| $p_T^V$ from NLO EW correction | M+S |

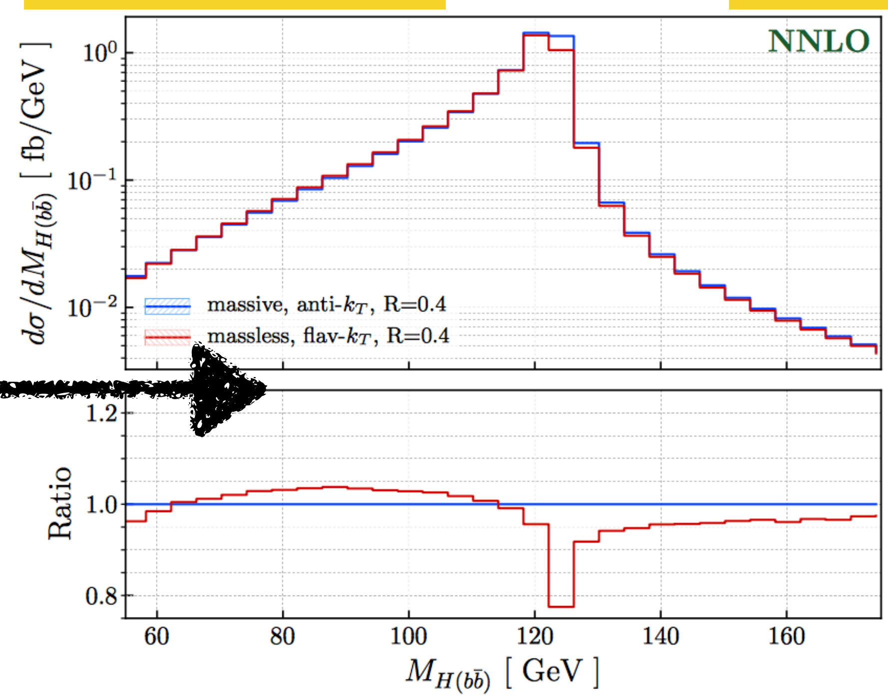
**ATLAS & CMS**: Hbb BR/decay using Pythia8 for the decay. Uncertainty on BR from YR

Decay in Hbb known at N3LO with inclusion of effects due to finite botton-quark mass in NNLO predictions

R. Mondini, C. Williams et al

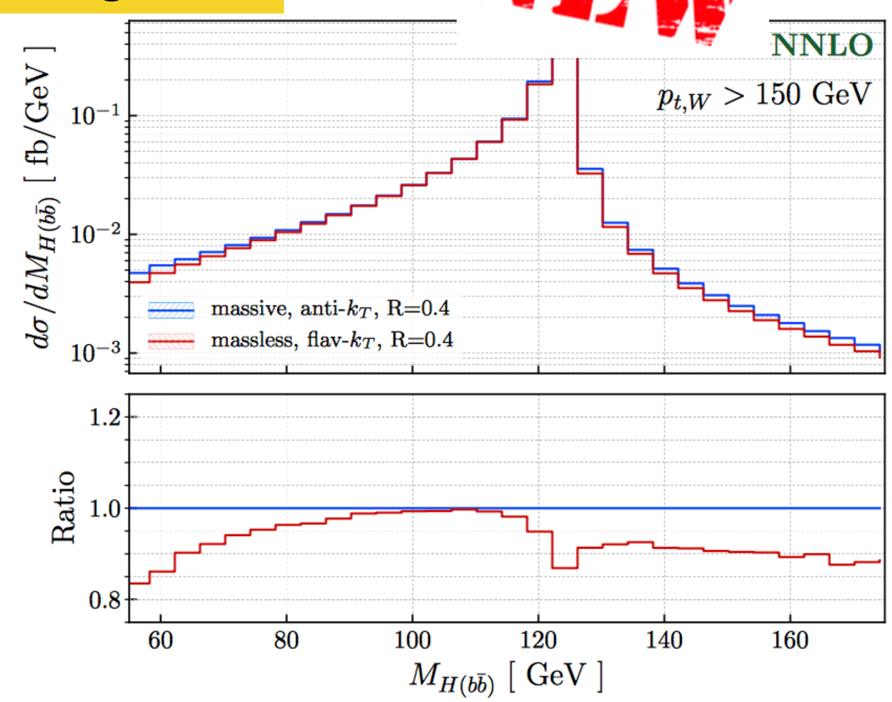
- Finite b-quark mass calculation on NNLO has large impact on m(bb) lineshape modelling especially in high pt
- Interesting to check impact on analysis to test if the effect is already accounted for by PS

W. Astill et al.




A. Behring et al

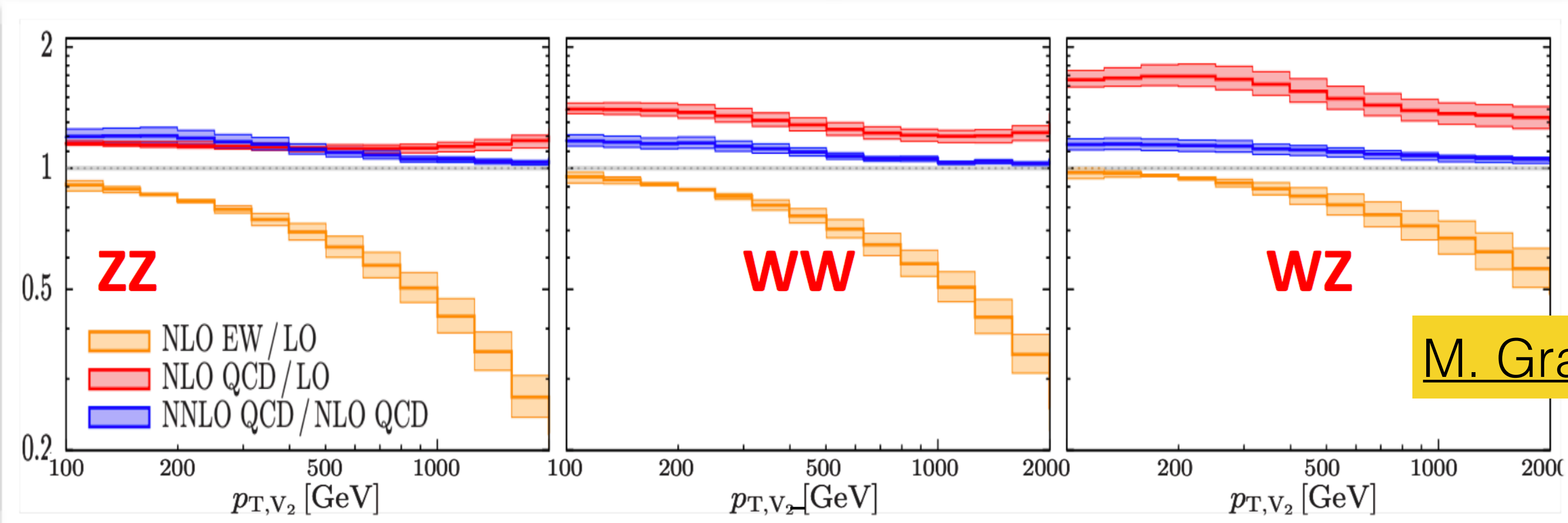
NEW



# Background modeling

# Non V+X backgrounds: VV, ttbar, single-top modeling

- Diboson cross-section constrained with a dedicated cross-check VZ→bb (WZ/ZZ) analysis
  - signal extraction compatible with SM and good modelling of observables, no concern on prediction
  - NLO VV production used by CMS with fully leptonic diboson EWK correctionsn




M. Grazzini et al.

- ttbar and single-top modelling achieved with different approaches in ATLAS and CMS
  - CMS: MC-based analysis (PP8) and dedicated tt-enriched control regions to constrain shape and normalisation with data; ATLAS: MC-based measurement with addition of data-driven techniques in 2lep channel
  - Studies by ATLAS on 0/1lep and boosted Hbb regarding tt ptV spectrum using PP8 [link]
  - PP8 DS found to provide better agreement with data
  - no problematic issues in MC predictions - post-fit process rate parameters for ttbar processes always close to unity and largely constrained due to excellent purity of tt-enriched regions

# V+jets modeling



ATLAS 2007.02873

| Source of uncertainty | | $\sigma_\mu$ VH | WH | ZH |
|---|---|---|---|---|
| Total | | 0.177 | 0.260 | 0.240 |
| Statistical | | 0.115 | 0.182 | 0.171 |
| Systematic | | 0.134 | 0.186 | 0.168 |
| **Statistical uncertainties** | | | | |
| Data statistical | | 0.108 | 0.171 | 0.157 |
| $t\bar{t}$ $e\mu$ control region | | 0.014 | 0.003 | 0.026 |
| Floating normalisations | | 0.034 | 0.061 | 0.045 |
| **Experimental uncertainties** | | | | |
| Jets | | 0.043 | 0.050 | 0.057 |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ | | 0.015 | 0.045 | 0.013 |
| Leptons | | 0.004 | 0.015 | 0.005 |
| $b$-tagging | $b$-jets | 0.045 | 0.025 | 0.064 |
| | $c$-jets | 0.035 | 0.068 | 0.010 |
| | light-flavour jets | 0.009 | 0.004 | 0.014 |
| Pile-up | | 0.003 | 0.002 | 0.007 |
| Luminosity | | 0.016 | 0.016 | 0.016 |
| **Theoretical and modelling uncertainties** | | | | |
| Signal | | 0.072 | 0.060 | 0.107 |
| $Z$ + jets | | 0.032 | 0.013 | 0.059 |
| $W$ + jets | | 0.040 | 0.079 | 0.009 |
| $t\bar{t}$ | | 0.021 | 0.046 | 0.029 |
| Single top quark | | 0.019 | 0.048 | 0.015 |
| Diboson | | 0.033 | 0.033 | 0.039 |
| Multi-jet | | 0.005 | 0.017 | 0.005 |
| MC statistical | | 0.031 | 0.055 | 0.038 |

CMS 1808.08242

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| Signal modeling | +0.07 | −0.04 |
| Total | +0.35 | −0.33 |

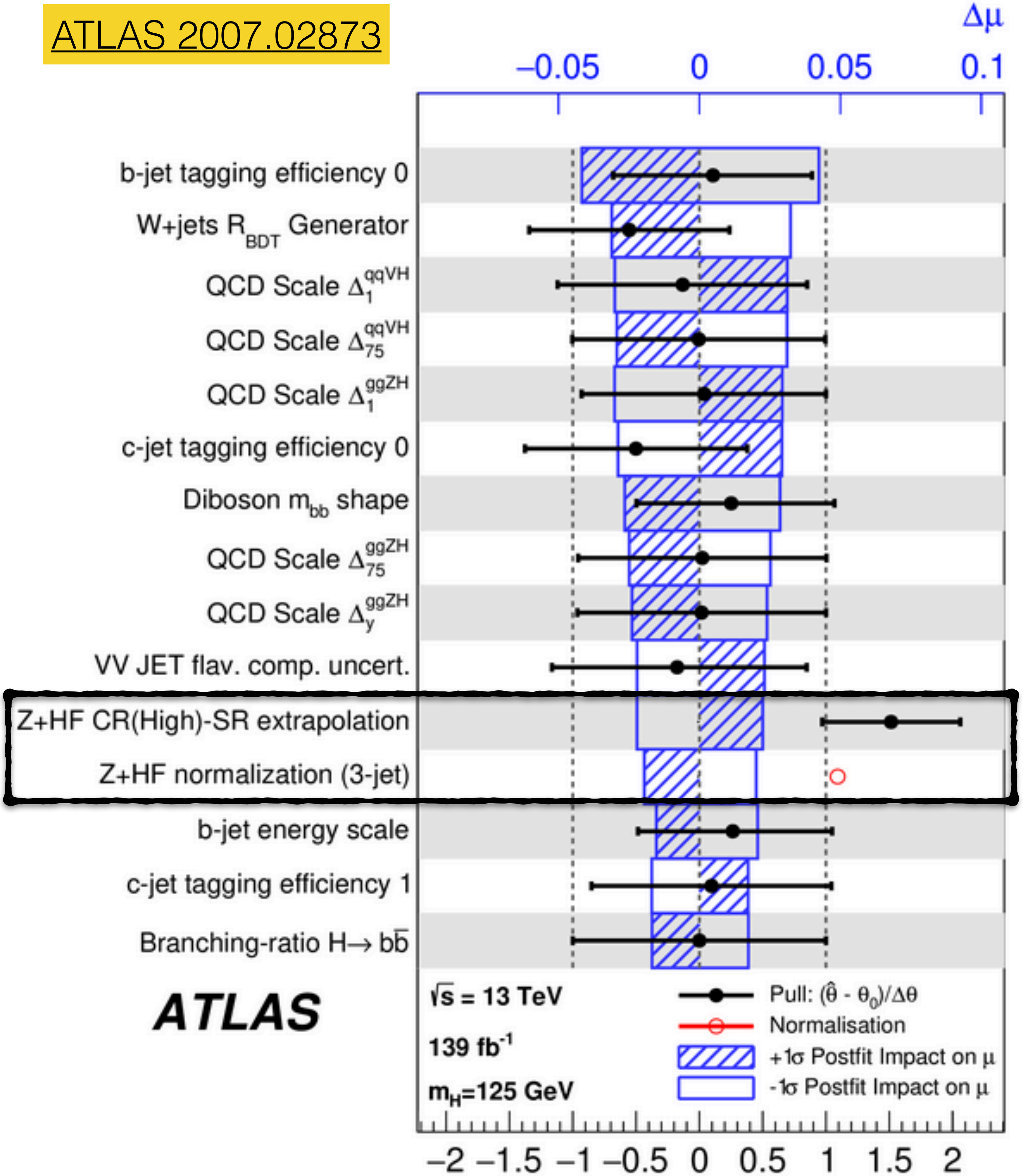
➡ V+heavy-flavour represents the main irreducible background of the VHbb analysis

- theory prediction extremely important for accurate signal extraction
- data constrains prediction of V+jets processes very precisely → MC modelling and choice of systematics variations can impact the measurement significantly

# V+jets modeling (2)

NEW

ATLAS 2007.02873




➡ Different strategies in ATLAS and CMS on V+jets

- modelling of MC prediction
- associated modelling uncertainties
- phase-space for rate-parameter constraints

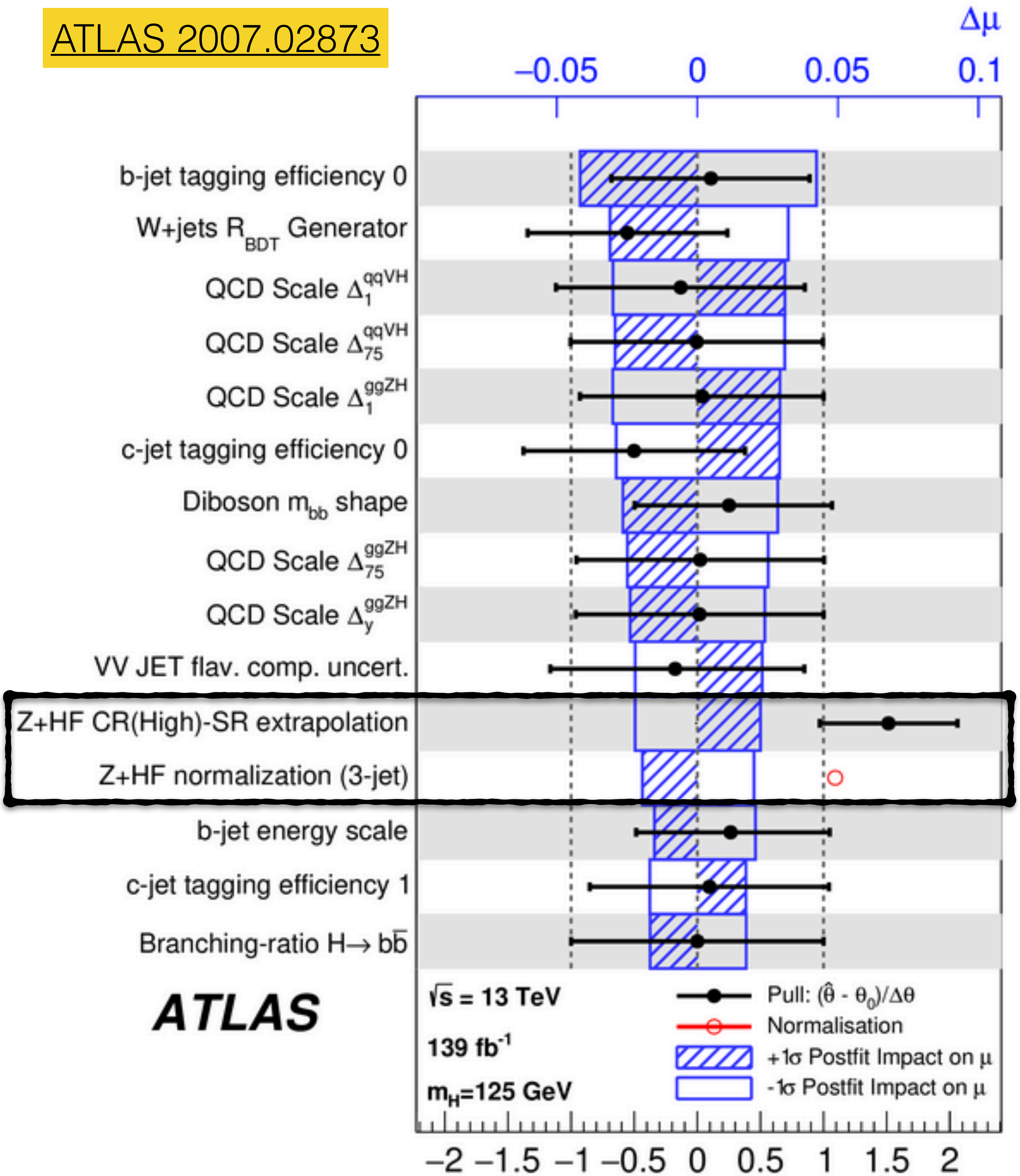
| | CMS | ATLAS |
|---|---|---|
| V+jets nominal | MadGraph V+jets @ LO (HT+bEnriched) | Sherpa V+jets @ NL (0, 1, 2j) +3, 4j@LO |
| Reweightings | VPT EWK corrections+NLO/LO Δη(bb) reweighing + uncertainties | / |

ATLAS/CMS comparison of V+jets predictions is far from trivial!

# V+jets modeling (3)

NEW

ATLAS 2007.02873




➡ Different strategies in ATLAS and CMS on V+jets

- modelling of MC prediction
- associated modelling uncertainties
- phase-space for rate-parameter constraints

| | |
|---|---|
| CMS | HF-enriched CR's based on HFDNN multiclassifer, DeepCSV discriminant in 2lep for separate STXS VPT bins |
| ATLAS | CR's defined using ΔR(bb) for separate jet multiplicities and STXS VPT bins |

ATLAS/CMS comparison of V+jets predictions is far from trivial!

# V+jets modeling (4)

- Normalisation of V+jets background extracted from data by freely-floating the corresponding rate parameters in the simultaneous ML fit of SR and CR
  - significant differences in data wrt MC pre-fit predictions
  - difference in phase-space definition for CR constraints of process scale factors between ATLAS and CMS make the comparison not very trivial
  - need for harmonisation of phase-space definition, objects to ensure meaningful comparison of background process scale factors in ATLAS and CMS

ATLAS 2007.02873

| Process and Category | Normalisation factor |
|---|---|
| $t\bar{t}$ 2-jet | $0.98 \pm 0.09$ |
| $t\bar{t}$ 3-jet | $0.93 \pm 0.06$ |
| $W$ + HF 2-jet | $1.06 \pm 0.11$ |
| $W$ + HF 3-jet | $1.15 \pm 0.09$ |
| $Z$ + HF 2-jet, $75 < p_T^V < 150$ GeV | $1.28 \pm 0.08$ |
| $Z$ + HF 3-jet, $75 < p_T^V < 150$ GeV | $1.17 \pm 0.05$ |
| $Z$ + HF 2-jet, 150 GeV $< p_T^V$ | $1.16 \pm 0.07$ |
| $Z$ + HF 3-jet, 150 GeV $< p_T^V$ | $1.09 \pm 0.04$ |

CMS 1808.08242

| Process | $Z(\nu\nu)H$ | $W(\ell\nu)H$ | $Z(\ell\ell)H$ low-$p_T$ | $Z(\ell\ell)H$ high-$p_T$ |
|---|---|---|---|---|
| W + udscg | $1.04 \pm 0.07$ | $1.04 \pm 0.07$ | | |
| W + b | $2.09 \pm 0.16$ | $2.09 \pm 0.16$ | | |
| W + $b\bar{b}$ | $1.74 \pm 0.21$ | $1.74 \pm 0.21$ | – | – |
| Z + udscg | $0.95 \pm 0.09$ | – | $0.89 \pm 0.06$ | $0.81 \pm 0.05$ |
| Z + b | $1.02 \pm 0.17$ | – | $0.94 \pm 0.12$ | $1.17 \pm 0.10$ |
| Z + $b\bar{b}$ | $1.20 \pm 0.11$ | – | $0.81 \pm 0.07$ | $0.88 \pm 0.08$ |

- Continuing V+HF modeling studies in VH sub-group:
  - support/validation studies for nominal modelling of MC prediction of V+jets - important to check even at pre-fit level the difference in ATLAS/CMS V+jets predictions as done for TT [PUB note]
  - definition of common set of uncertainties associated to MC V+HF modelling

# Wrapping-up and conclusions

➡ Very fruitful interactions between theory and experimental community on several VH(bb)-related processes for signal and background modelling

- STXS-based categorisation and definition of associated uncertainties example of success of WG1 proposal
- VH modeling currently one of the main limitations to VH(bb) precision measurements
- improvement in VH modelling will dramatically impact key uncertainties of the analysis (ggZH signal, V+HF background modeling) and will largely benefit from further developments and studies within the LHC Higgs VH subgroup

➡ VH(bb) analyses have concluded or about to conclude cross-section measurement with full Run 2 dataset

- comparisons of analysis strategies and especially on the treatment of the V+jets background modelling of outmost importance

# Backup slides

# Signal uncertainties on STXS measurement



- QCD scale uncertainties parametrised as overall uncertainty component and migration uncertainties across bin-boundaries (in VPT and jet multiplicity)
    - migration uncertainties calculated as combination of renormalisation and factorisation scale
- Cross-section uncertainty become residual shape uncertainties with coarser STXS bins
- Maximal deviation split presented here