

# Overview of VH WG1 experimental/theory status

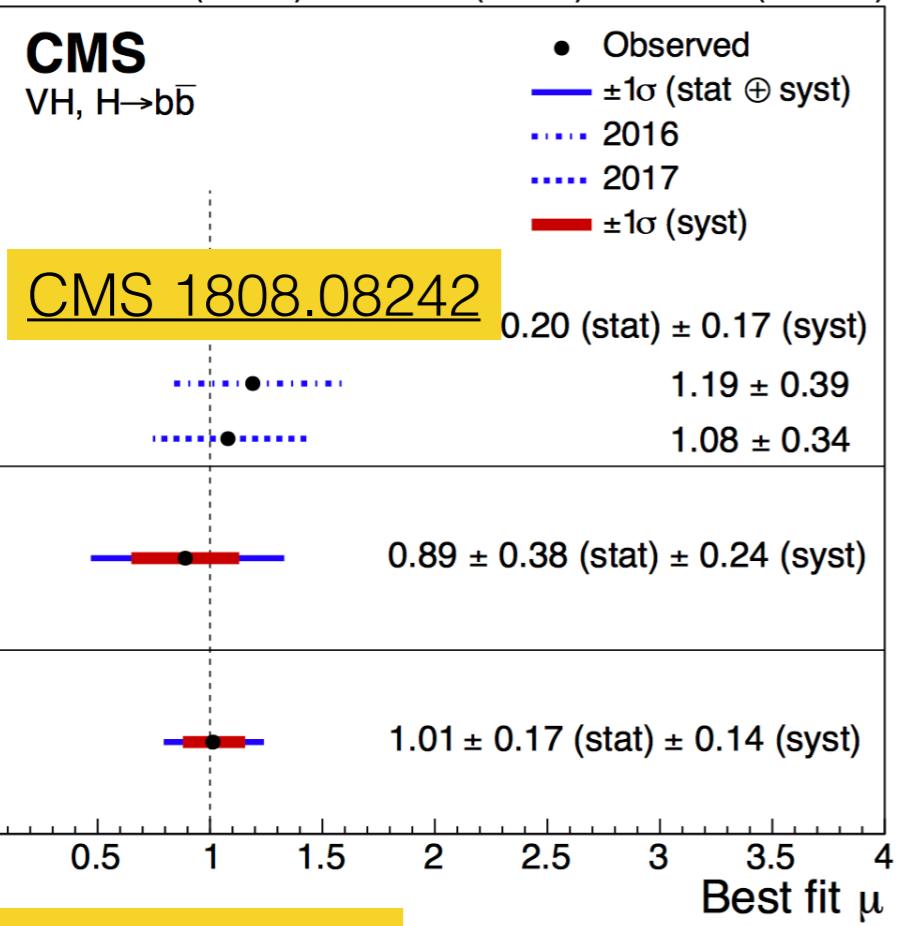
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C. Pandini (UniGe), P. Windischhofer (University of Oxford)

# Outline of the talk

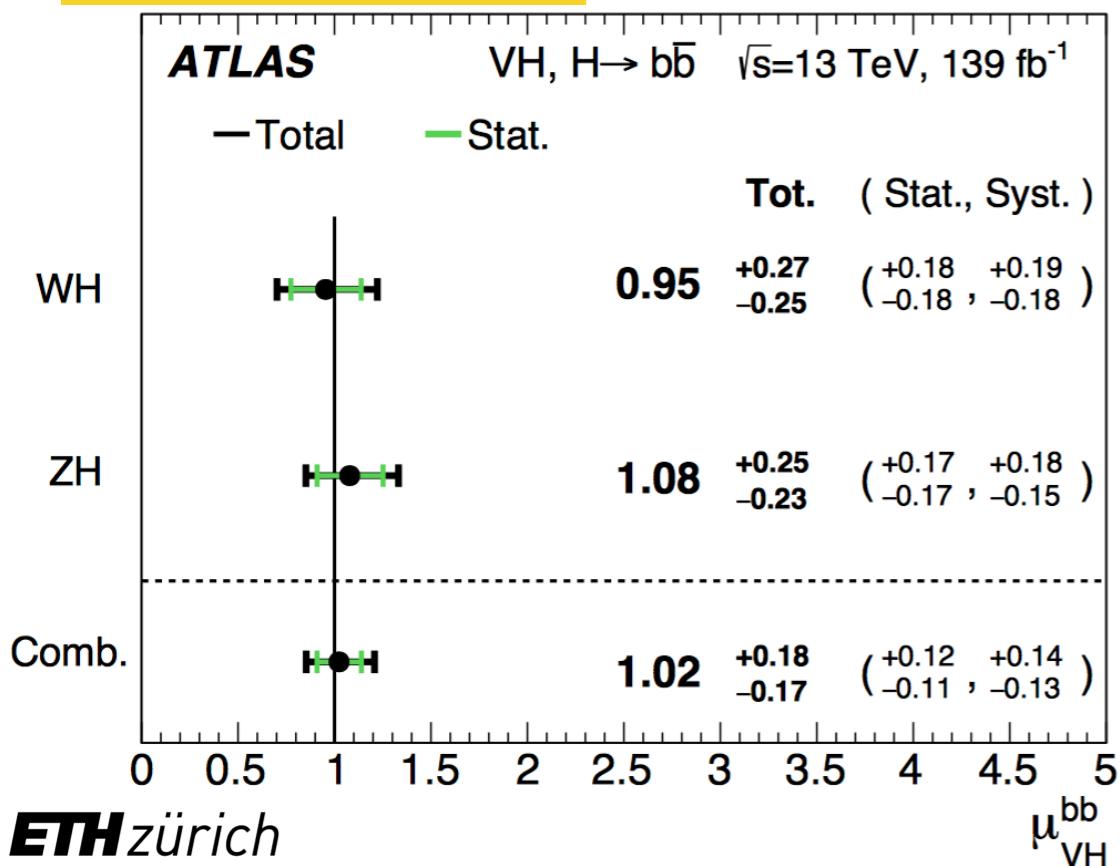
- ➡ LHC Higgs WG I - VH sub-group [[twiki](#)], WG I fall meeting at this [link](#)
- ➡ Quick overview of the state-of-the-art for ATLAS&CMS VHbb measurements
  - ▶ new developments wrt last LHC Higgs WG workshop [Nov 2020] marked as **NEW**
- ➡ VH signal uncertainties - theoretical developments and 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

5.1 fb<sup>-1</sup> (7 TeV) + 18.9 fb<sup>-1</sup> (8 TeV) + 77.2 fb<sup>-1</sup> (13 TeV)

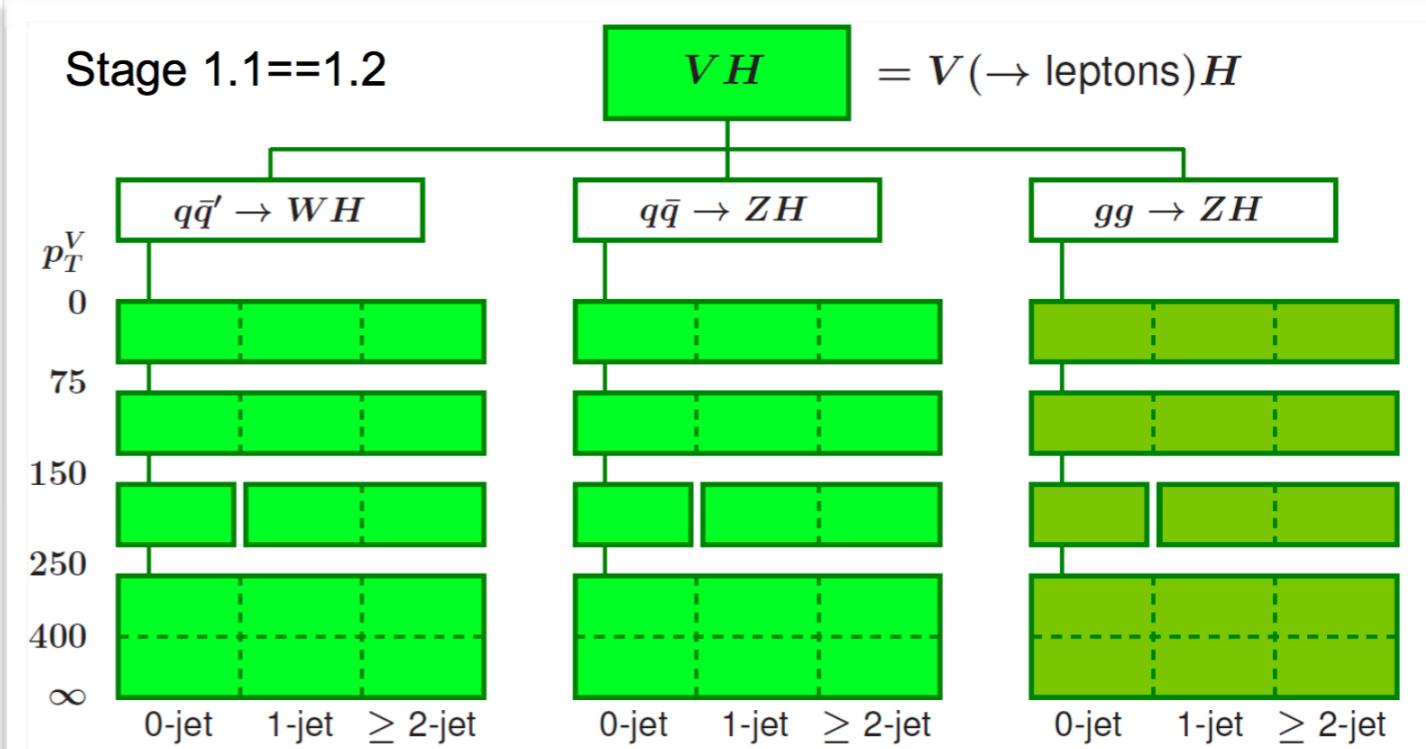


**ATLAS 2007.02873**



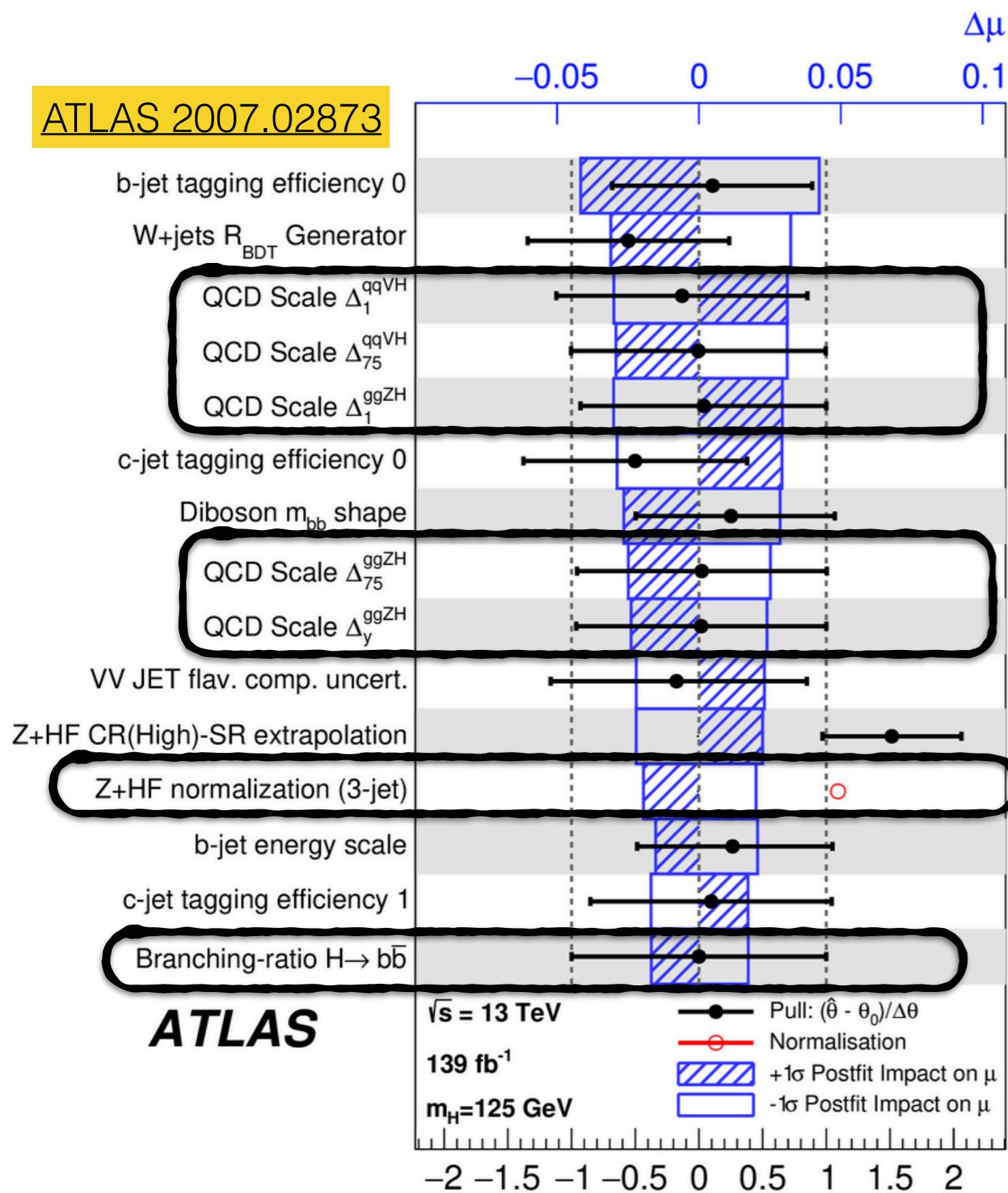
- Evolution of inclusive measurements - STXS approach categorises events at gen-level using analyses observables (ptV, ptH, nJet, ...)
- Signal extraction is optimised for kinematic features of specific bin
- Several points of interest for analysis sensitivity (bins to target, what to do with non-sensitive 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
Z+HF normalization (3-jet)	+0.08	-0.07
b-jet energy scale	+0.05	-0.05
c-jet tagging efficiency 1	+0.02	-0.01
Branching-ratio $H \rightarrow b\bar{b}$	+0.03	-0.03
Luminosity	+0.06	-0.05
Other experimental uncertainties	+0.12	-0.12
MC sample size	+0.11	-0.09
Theory	+0.08	-0.08
Background modeling	+0.07	-0.04
Signal modeling	+0.35	-0.33
Total	+0.35	-0.33

CMS 1808.08242

# Signal modeling

# Signal modeling of ggZH process

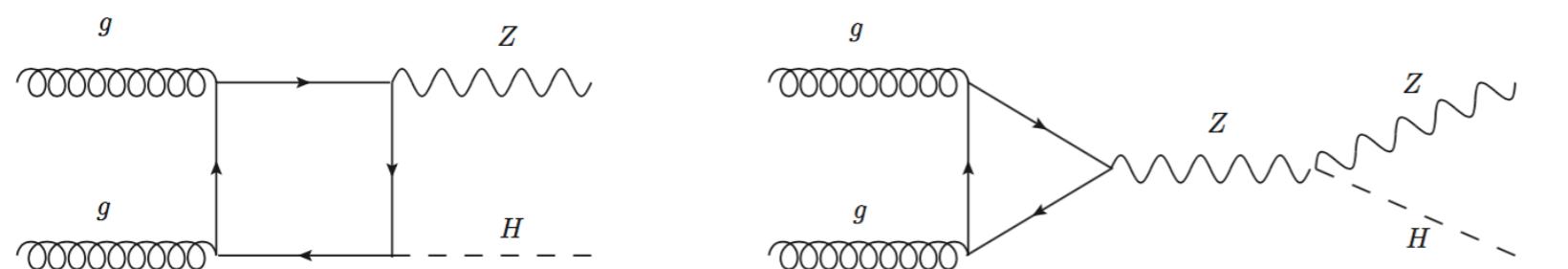
ATLAS 2007.02873

## Signal

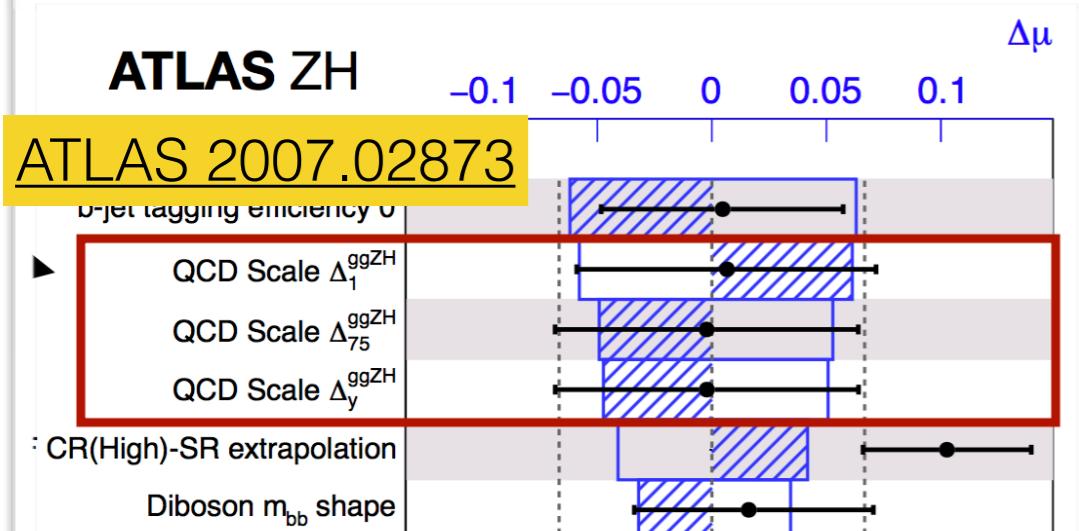
Cross-section (scale)  
 $H \rightarrow b\bar{b}$  branching fraction  
 Scale variations in STXS bins  
 PS/UE variations in STXS bins  
 PDF+ $\alpha_S$  variations in STXS bins  
 $m_{bb}$  from scale variations  
 $m_{bb}$  from PS/UE variations  
 $m_{bb}$  from PDF+ $\alpha_S$  variations  
 $p_T^V$  from NLO EW correction

0.7% ( $qq$ ), 25% ( $gg$ )  
 1.7%  
 3.0%–3.9% ( $qq \rightarrow WH$ ), 6.7%–12% ( $qq \rightarrow ZH$ ), 37%–100% ( $gg \rightarrow ZH$ )  
 1%–5% for  $qq \rightarrow VH$ , 5%–20% for  $gg \rightarrow VH$   
 1.8%–2.2% ( $qq \rightarrow WH$ ), 1.4%–1.7% ( $qq \rightarrow ZH$ ), 2.9%–3.3% ( $gg \rightarrow ZH$ )  
 M+S ( $qq \rightarrow VH$ ,  $gg \rightarrow ZH$ )  
 M+S  
 M+S  
 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



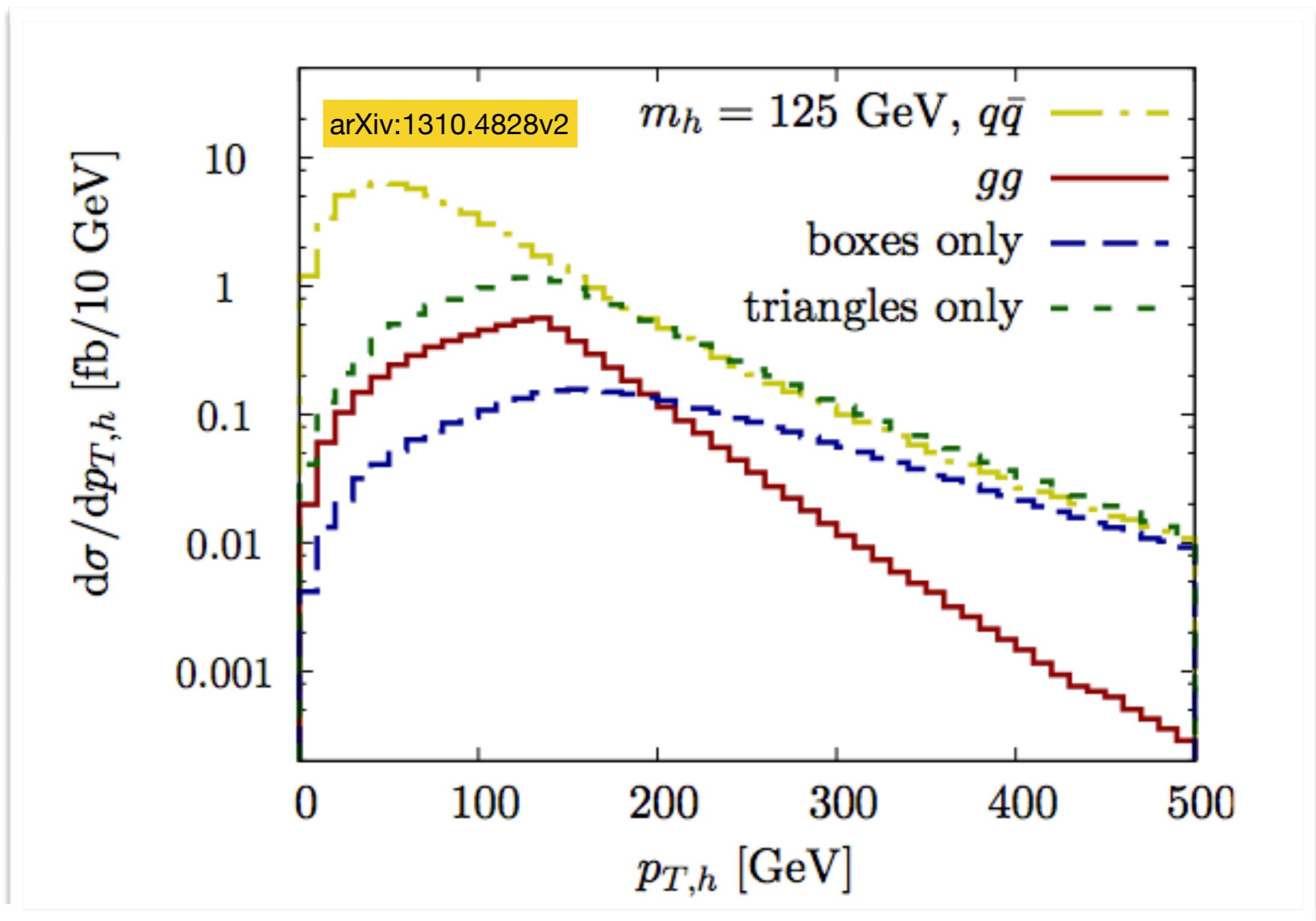
ggZH uncertainties (QCD scale) largely impactful at pre- and post-fit level

Process	Cross Section (pb)	+QCD Scale %	-QCD Scale %	$\pm(\text{PDF}+\alpha_S) \%$	$\pm\text{PDF} \%$	$\pm\alpha_S \%$
$pp \rightarrow ZH$	0.8839	+3.8%	-3.1%	$\pm 1.6\%$	$\pm 1.3\%$	$\pm 0.9\%$
$qq/qg \rightarrow ZH$ , $gg \rightarrow HZ + q\bar{q}$ (all but $gg \rightarrow ZH$ )	0.7612	+0.5%	-0.6%	$\pm 1.9\%$	$\pm 1.7\%$	$\pm 0.9\%$
$gg \rightarrow ZH$	0.1227	+25.1%	-18.9%	$\pm 2.4\%$	$\pm 1.8\%$	$\pm 1.6\%$

CERN YR4

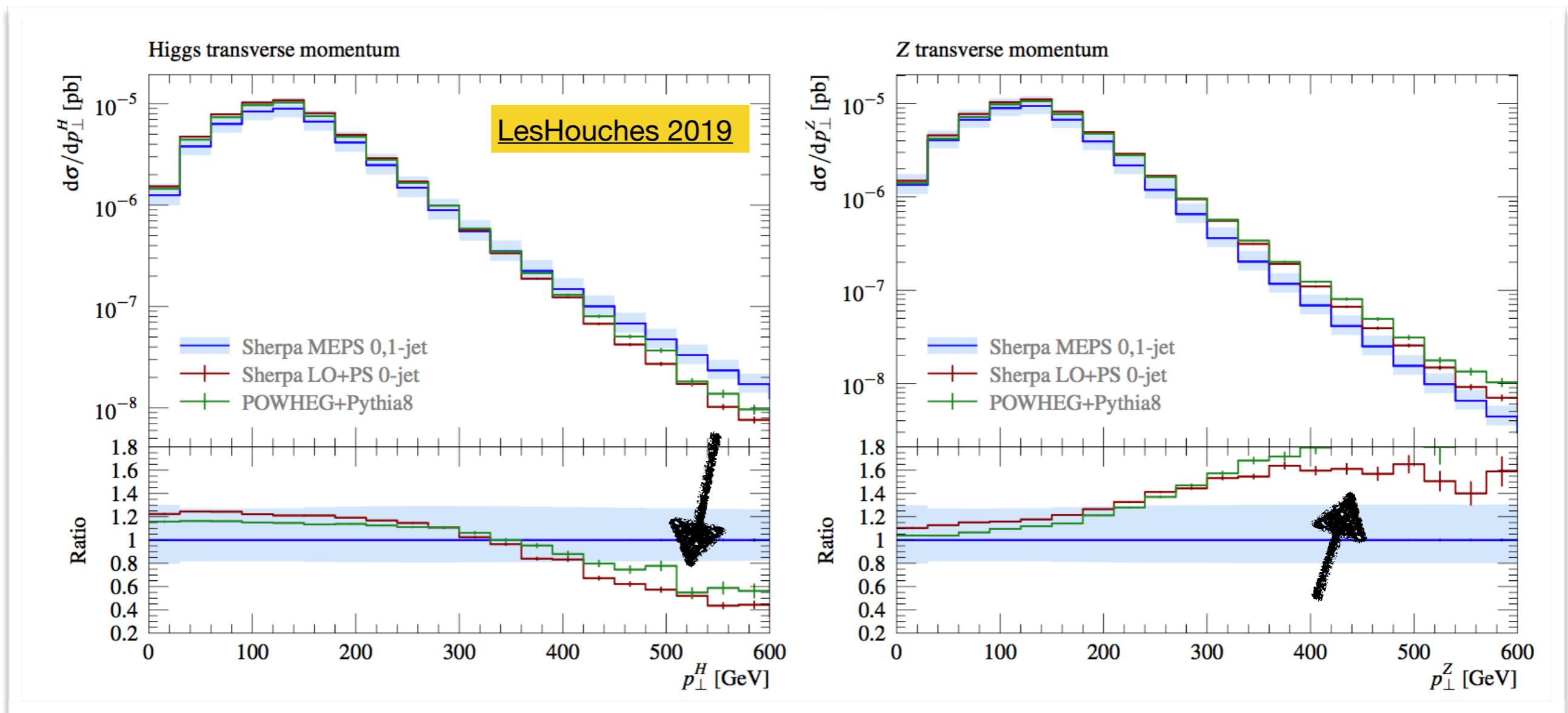
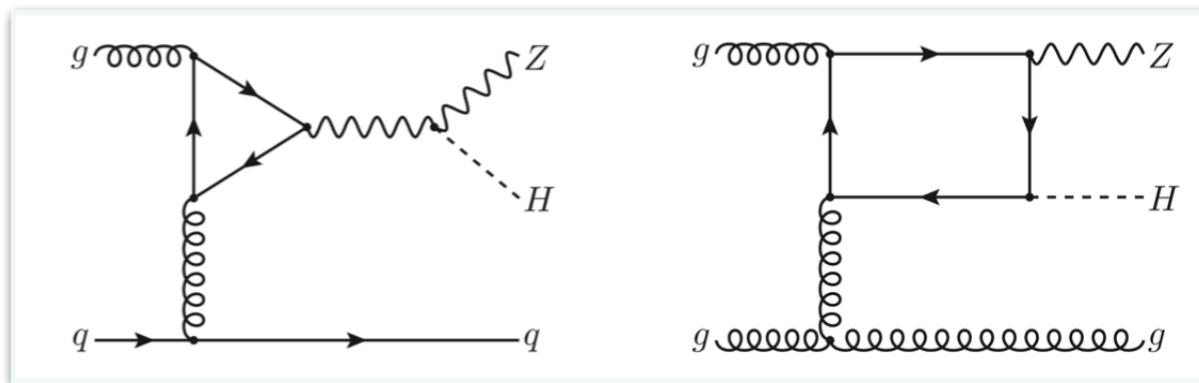
# Signal modeling of ggZH process

- 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

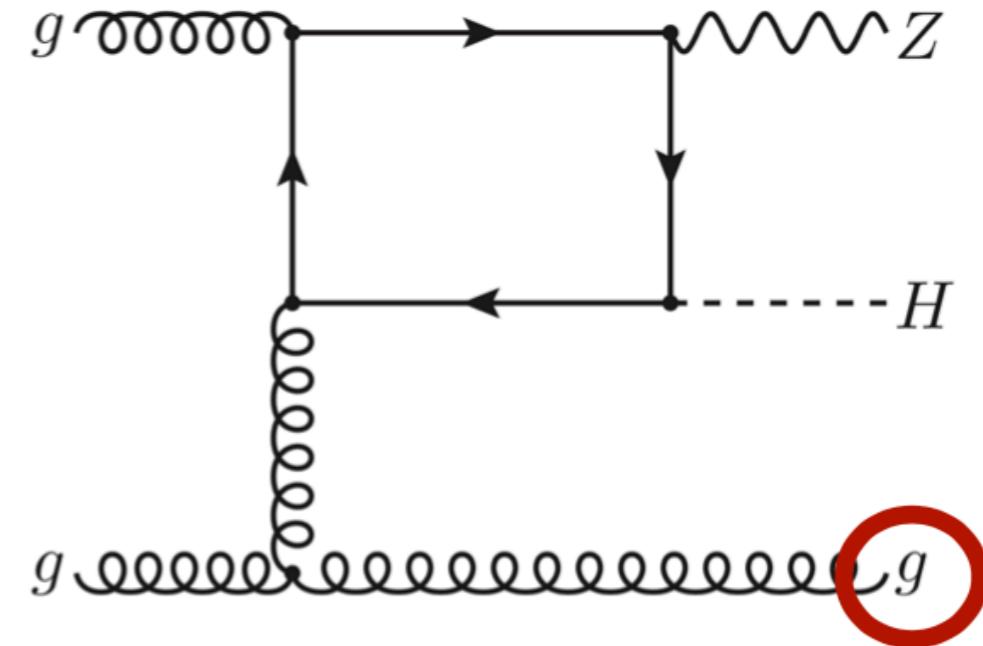
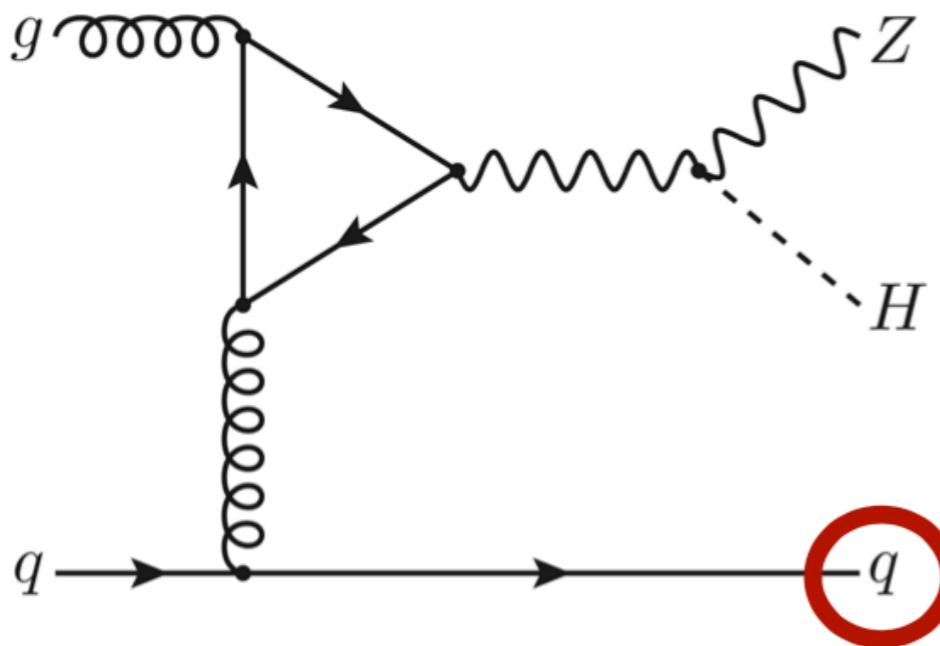
- Adding  $2 \rightarrow 3$  processes, i.e.  $gg \rightarrow ZH + 0, 1j$  merged prediction (Sherpa & MC@NLO).
- ▶ sizeable modifications in  $pT H/pT V$  spectra



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

# NEW Signal modeling of ggZH process in ATLAS

→ Goal: improve modelling of ggZH kinematics: add  $2 \rightarrow 3$  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

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

→ No dedicated uncertainty associated to PS comparisons for qqZH in ATLAS - expected smaller impact on signal extraction

→ 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

Uncertainty source	<u>CMS 1808.08242</u>	$\Delta\mu$
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

# Signal modeling of branching ratios and Hbb decays

ATLAS 2007.02873

## Signal

Cross-section (scale)	0.7% ( $qq$ ), 25% ( $gg$ )
$H \rightarrow b\bar{b}$ branching fraction	1.7%
Scale variations in STXS bins	3.0%–3.9% ( $qq \rightarrow WH$ ), 6.7%–12% ( $qq \rightarrow ZH$ ), 37%–100% ( $gg \rightarrow ZH$ )
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PDF+ $\alpha_S$ variations in STXS bins	1.8%–2.2% ( $qq \rightarrow WH$ ), 1.4%–1.7% ( $qq \rightarrow ZH$ ), 2.9%–3.3% ( $gg \rightarrow ZH$ )
$m_{bb}$ from scale variations	M+S ( $qq \rightarrow VH$ , $gg \rightarrow ZH$ )
$m_{bb}$ 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:**  
Hbb BR/decay  
using Pythia8 -  
very similar  
uncertainties

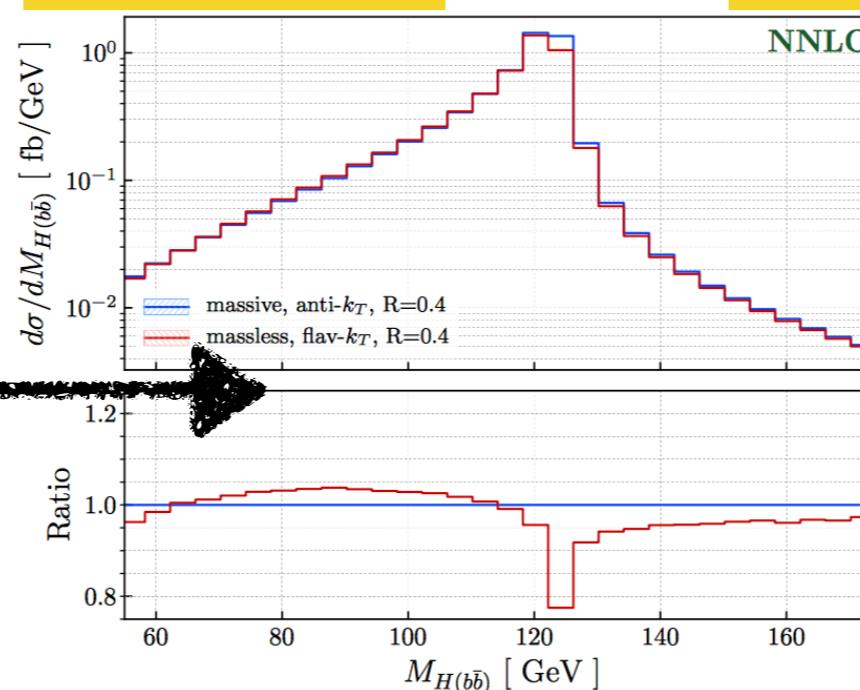
Decay in Hbb known at N3LO with inclusion of effects due to finite bottom-quark mass in NNLO predictions

R. Mondini, C. Williams et al

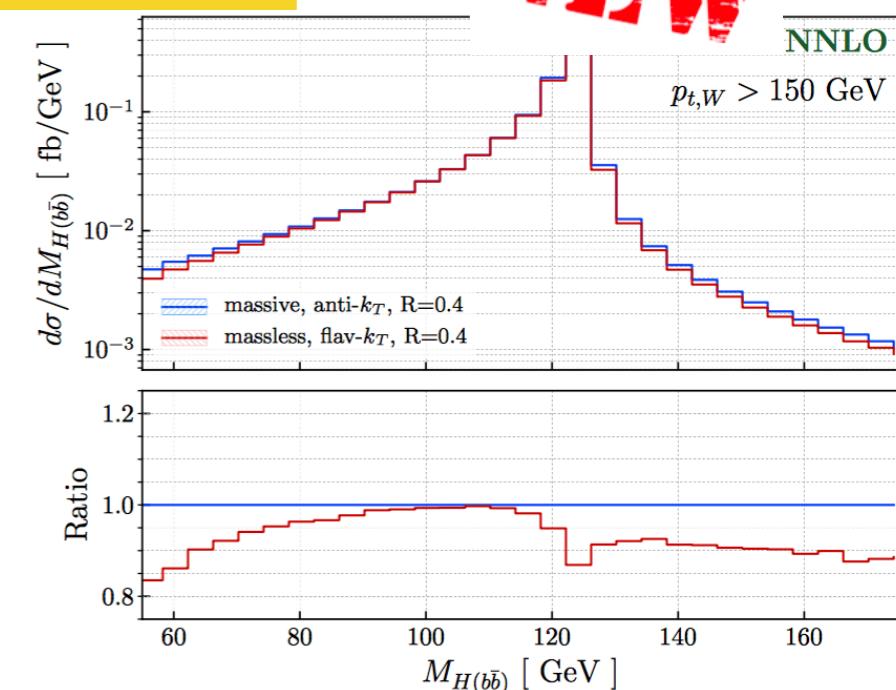
→ Finite b-quark mass calculation on NNLO has large impact on  $m(bb)$  lineshape modelling especially in high  $p_T$

→ 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



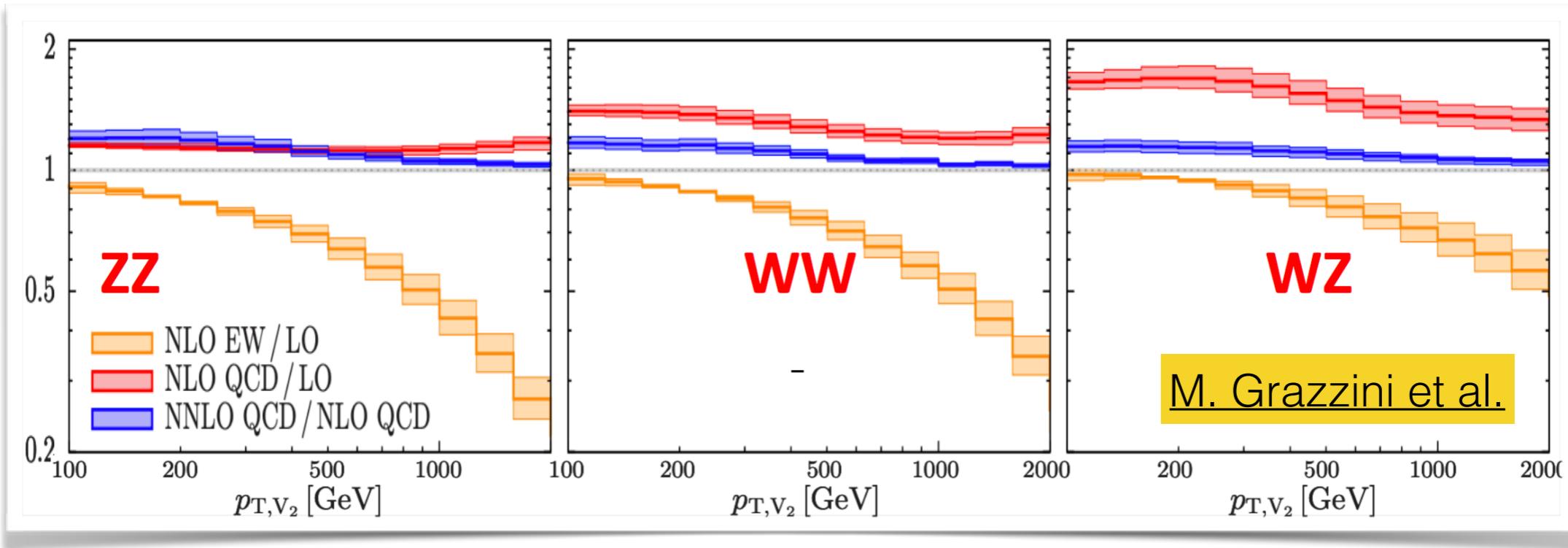
**NEW**

# Background modeling

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

→ Diboson cross-section constrained with a dedicated cross-check  $VZ \rightarrow bb$  ( $WZ/ZZ$ ) analysis

- ▶ signal extraction compatible with SM and good modelling of observables, no concern on prediction
- ▶ NLO VV production used by ATLAS and CMS with fully leptonic diboson EWK corrections using Matrix+OpenLoops reducing overall VV cross-section



→ 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
- ▶ no problematic issues in Monte Carlo predictions and modelling - post-fit process rate parameters for ttbar processes always close to unity and largely constrained due to excellent purity of tt-enriched regions

ATLAS 2007.02873

# V+jets modeling

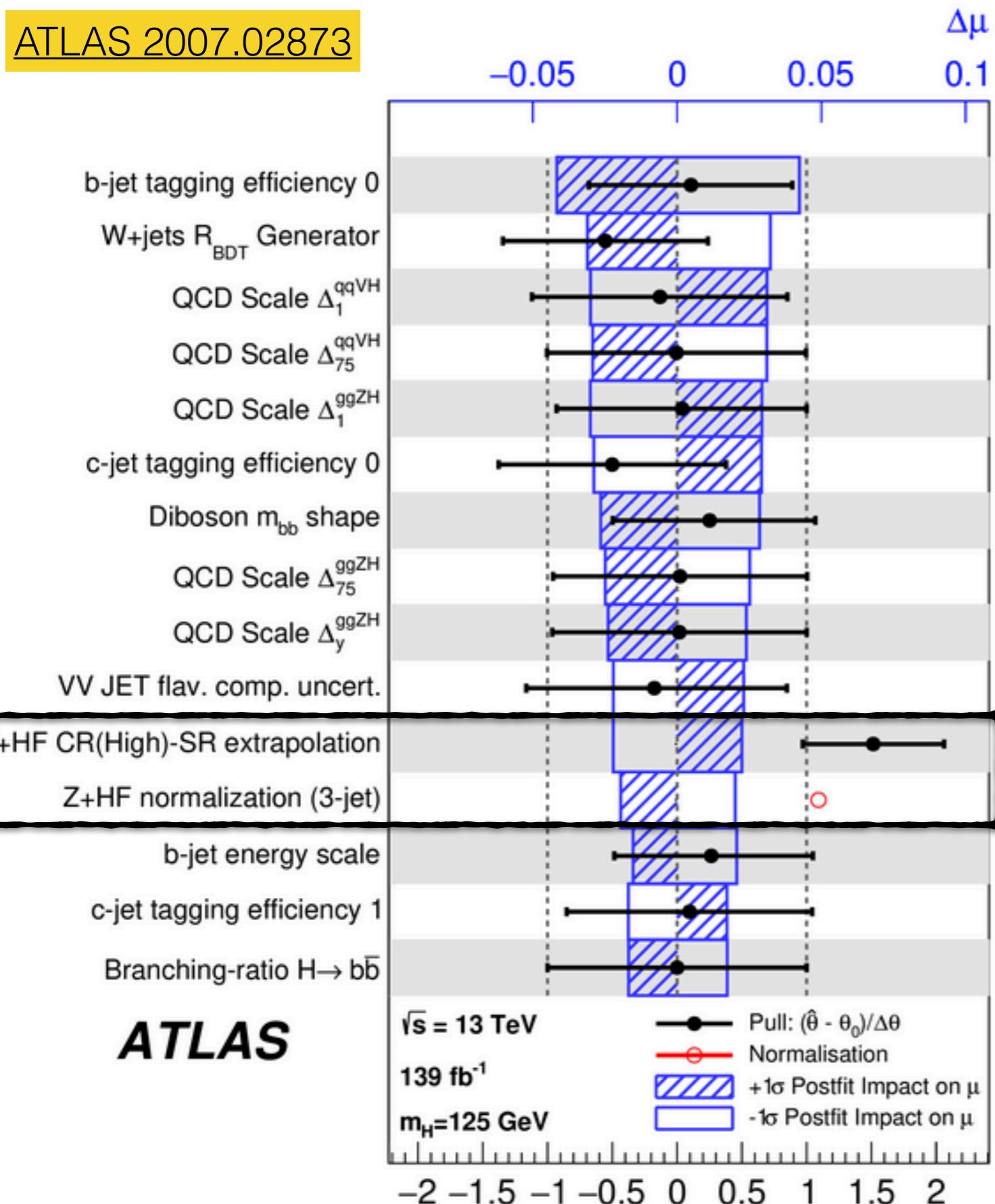
Source of uncertainty	$VH$	$\sigma_\mu$	$WH$	$ZH$
Total	0.177	0.260	0.240	
Statistical	0.115	0.182	0.171	
Systematic	0.134	0.186	0.168	
Statistical uncertainties				
Data statistical	0.108	0.171	0.157	
$t\bar{t} e\mu$ control region	0.014	0.003	0.026	
Floating normalisations	0.034	0.061	0.045	
Experimental uncertainties				
Jets	0.043	0.050	0.057	
$E_T^{\text{miss}}$	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	
$Z + \text{jets}$	0.032	0.013	0.059	
$W + \text{jets}$	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	

Uncertainty source	CMS 1808.08242	$\Delta\mu$
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Theory	+0.11	-0.09
Background modeling	+0.08	-0.08
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

**NEW**

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→ Different strategies in ATLAS and CMS on  $V + \text{jets}$

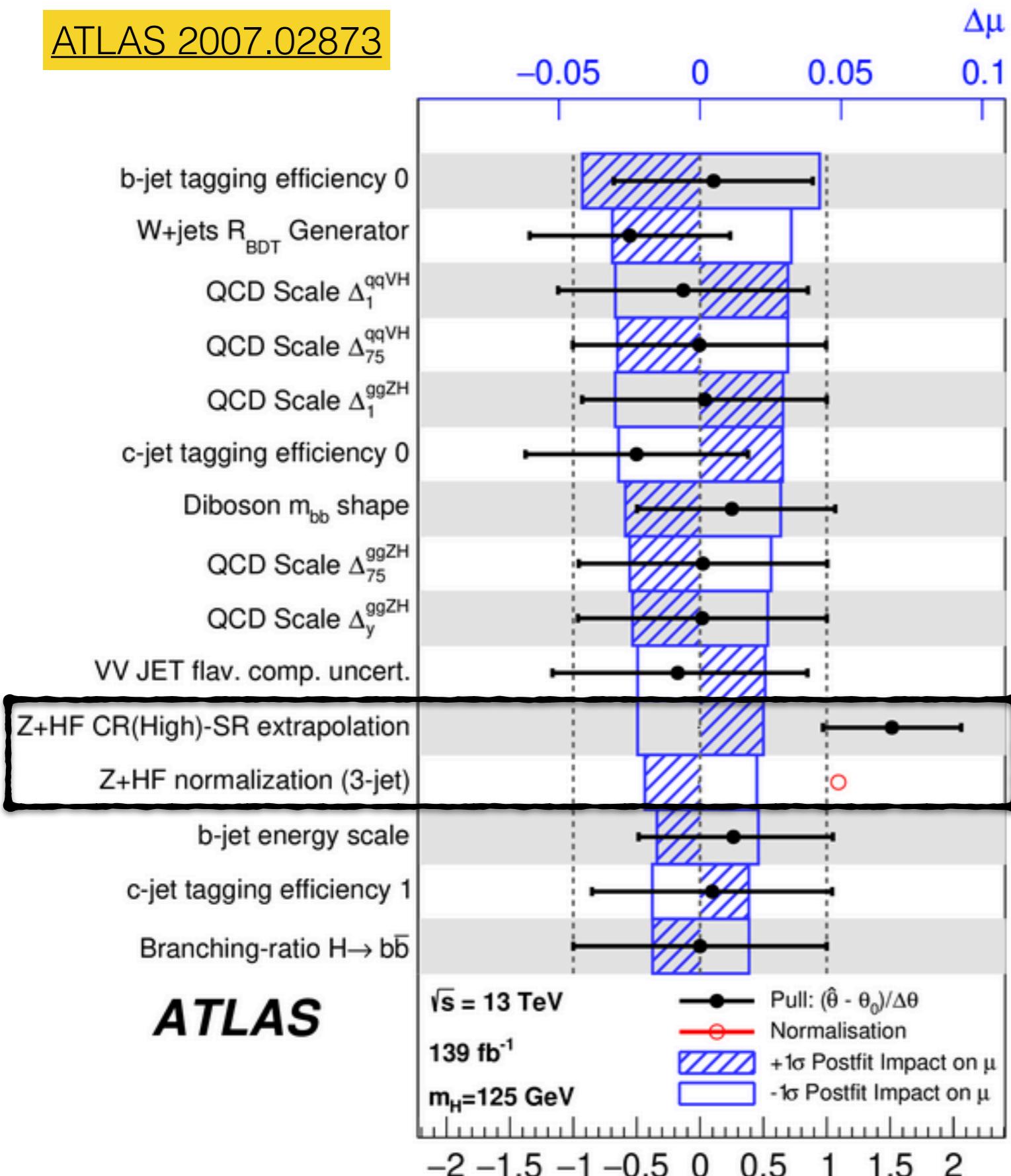
- ▶ modelling of MC prediction
- ▶ associated modelling uncertainties
- ▶ phase-space for rate-parameter constraints

	CMS	ATLAS
V+jets nominal	MadGraph V+jets @ LO (HT+bEnriched)	Sherpa V+jets @ NL (0, 1, 2j) +3, 4j@LO
Reweighting	VPT EWK corrections+NL O/LO $\Delta\eta(bb)$ reweighting + uncertainties	/

ATLAS/CMS comparison of  $V + \text{jets}$  predictions is far from trivial!

# V+jets modeling (3)

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 multiclassifier, DeepCSV discriminant in 2lep for separate STXS VPT bins
ATLAS	CR's defined using $\Delta R(bb)$ 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

Process and Category	Normalisation factor				
$t\bar{t}$ 2-jet	<u>ATLAS 2007.02873</u>	$0.98 \pm 0.09$			
$t\bar{t}$ 3-jet		$0.93 \pm 0.06$			
$W + \text{HF}$ 2-jet		$1.06 \pm 0.11$			
$W + \text{HF}$ 3-jet		$1.15 \pm 0.09$			
$Z + \text{HF}$ 2-jet, $75 < p_T^V < 150$ GeV		$1.28 \pm 0.08$			
$Z + \text{HF}$ 3-jet, $75 < p_T^V < 150$ GeV		$1.17 \pm 0.05$			
$Z + \text{HF}$ 2-jet, $150 \text{ GeV} < p_T^V$		$1.16 \pm 0.07$			
$Z + \text{HF}$ 3-jet, $150 \text{ GeV} < p_T^V$		$1.09 \pm 0.04$			

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

- 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 WGI 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

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- ➡ 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](#)