Overview of VH WG1 experimental/theory status

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on behalf of the LHC Higgs VH WG1 sub-group

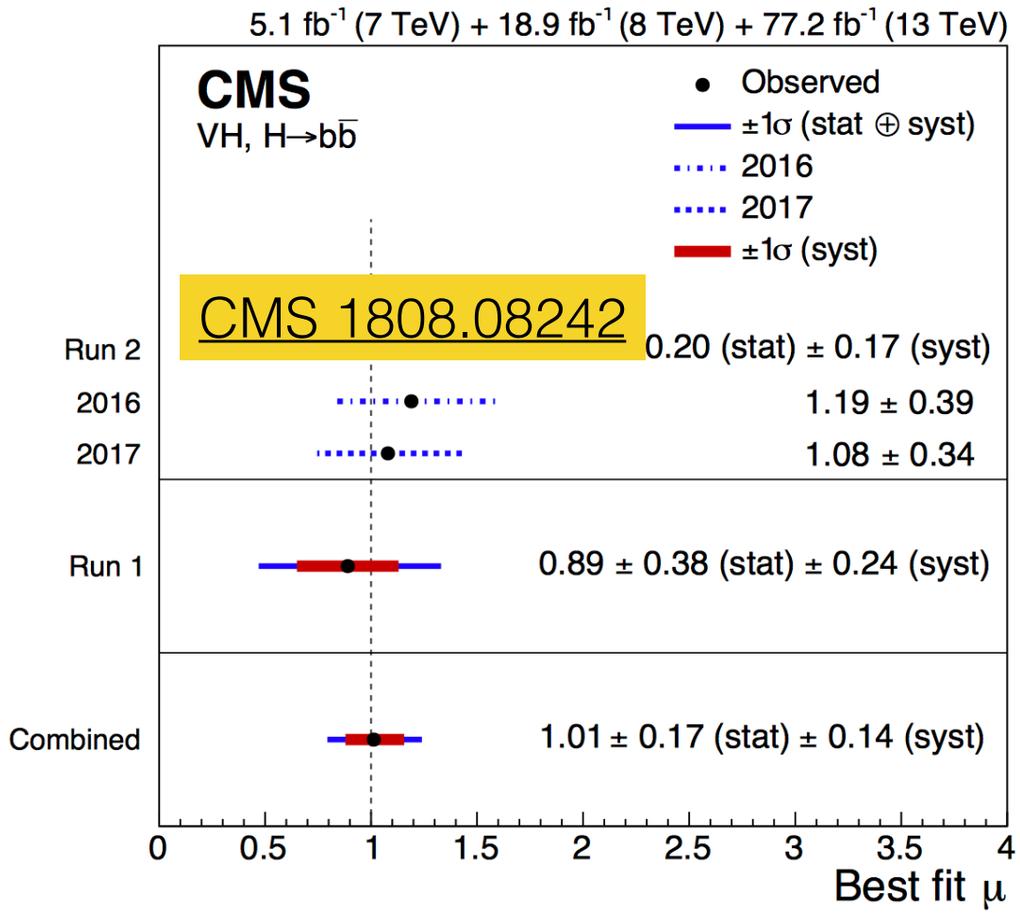
Workshop of the LHC Higgs Working group - December 1, 2021

Status of VH group activities and outline of the talk

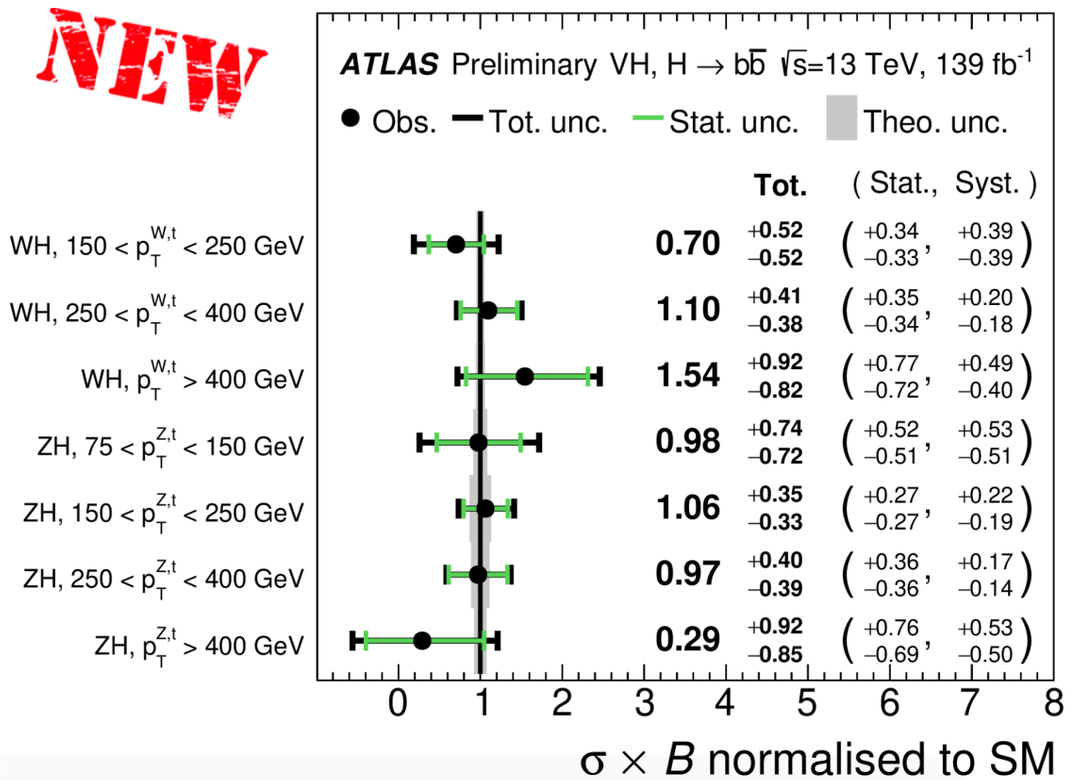
- LHC Higgs WG1 - VH sub-group [twiki], WG1 fall meeting at this link
  - after WG1 fall meeting in October, organised VH sub-group meeting [Nov. 8] focused on:
    - VHbb anomalous couplings at NNLO in QCD by R. Rontsch based on arXiv_2106.06328
    - discussion on status of experimental inputs/studies from ATLAS/CMS
    - plan to organise VH WG1 meeting beg. 2022 to touch base on ongoing theoretical efforts and on comparisons of experimental inputs especially for ATLAS/CMS VHbb analyses

- 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
  - non V+X backgrounds (backup), V+jets modelling - ATLAS/CMS comparison state-of-the art

Run 2 VHbb measurements - the state of the art



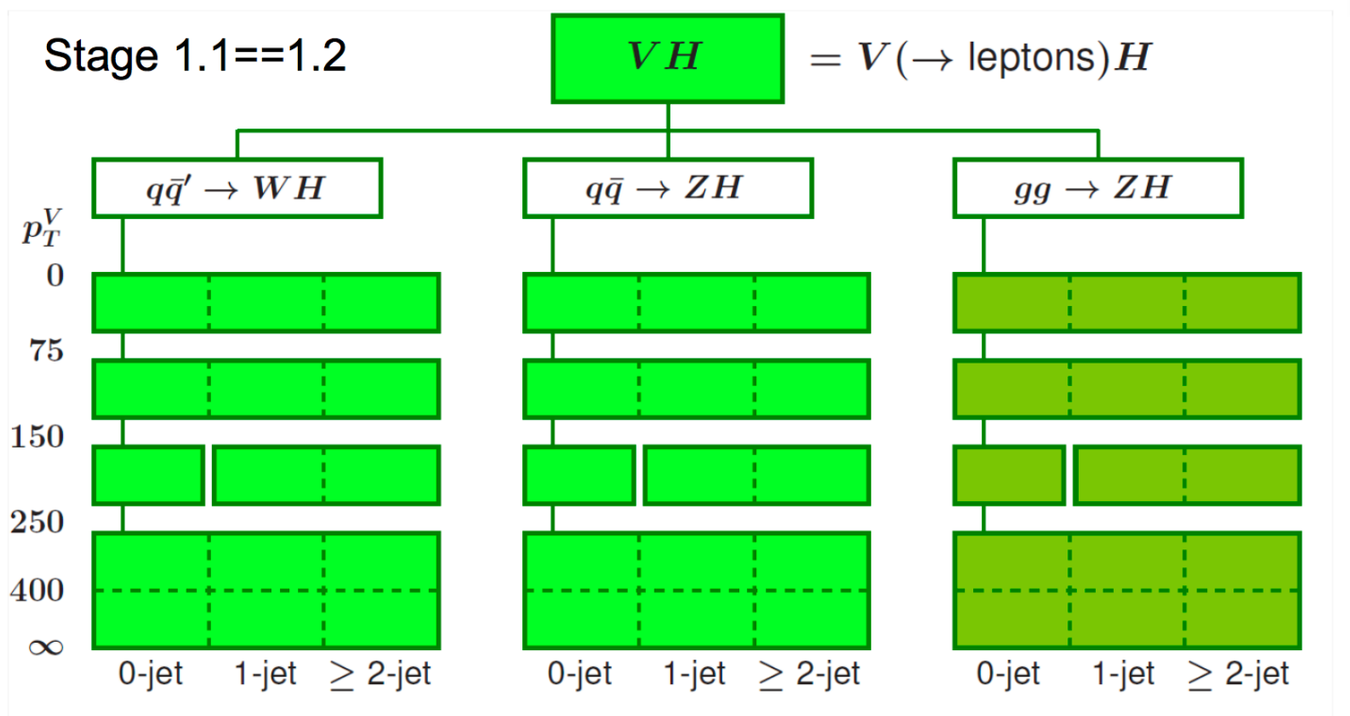
NEW



ATLAS-CONF-2021-051

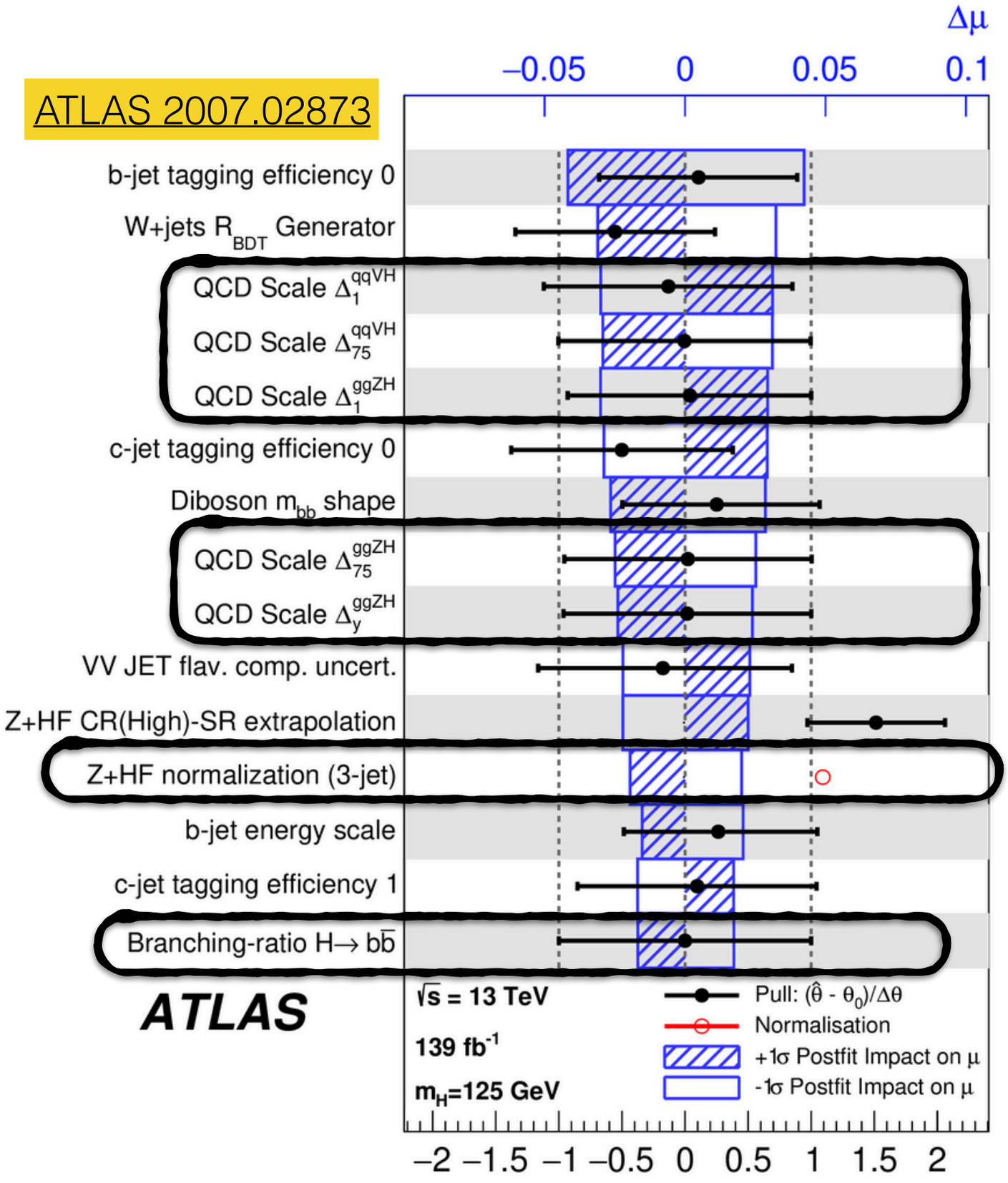
- Evolution of inclusive measurements - STXS approach categorises events at gen-level using analyses observables (ptV, ptH, nJet, …)
- Signal extraction is optimised for kinematic features of specific bin
- Several points of interest for analysis sensitivity (bins to target, what to do with non-sensitive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

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 $gg \to ZH$
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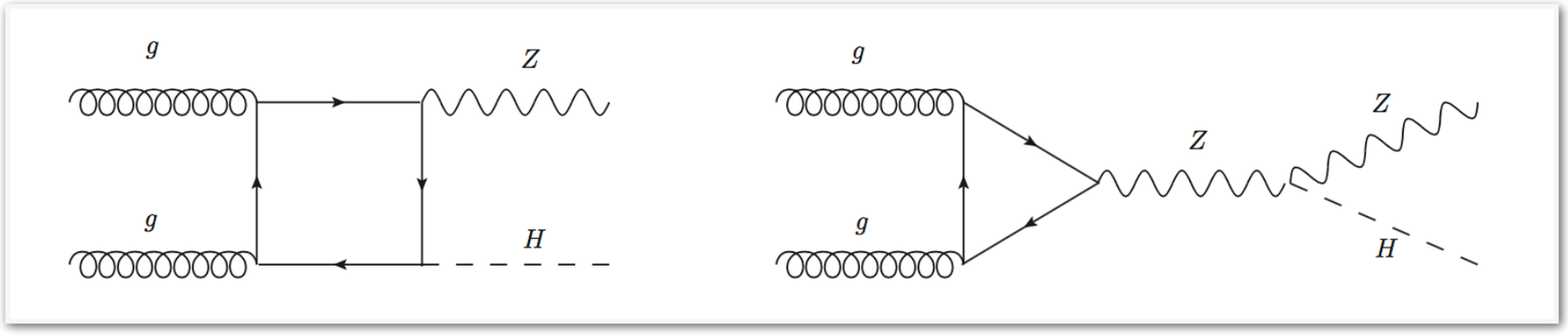
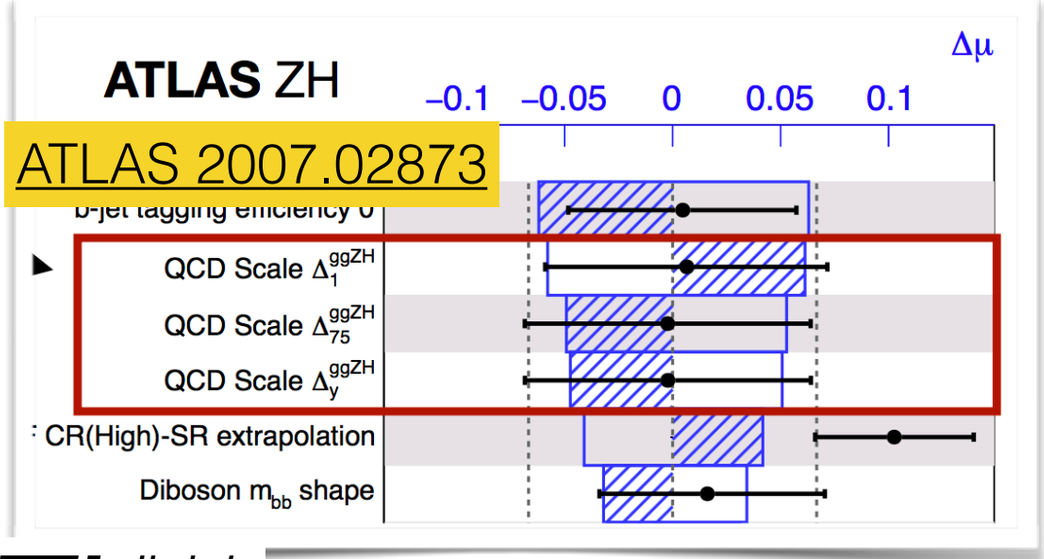
m_{bb} from scale variations	M+S ($qq \to VH$, $gg \to ZH$)
m_{bb} from PS/UE variations	M+S
m_{bb} from PDF+α_S variations	M+S
p_T^V from NLO EW correction	M+S

ATLAS & CMS:
Powheg ggZH@LO in QCD



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



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

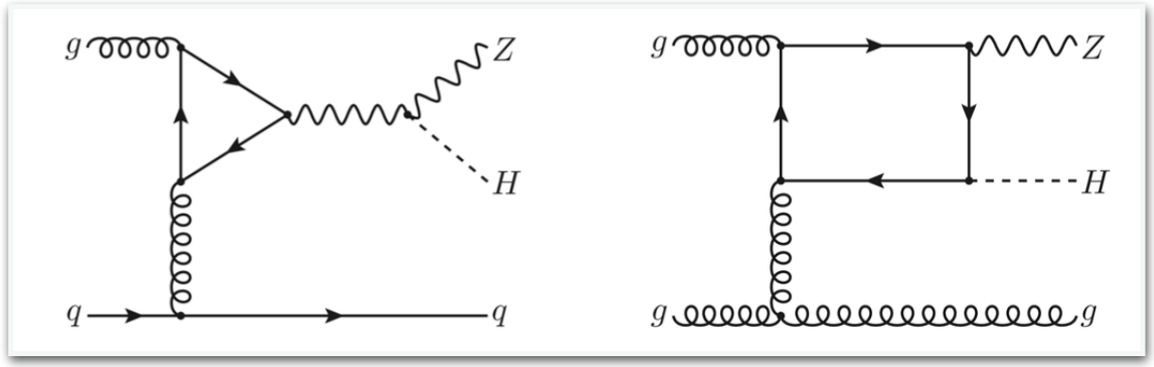
Process	Cross Section (pb)	+QCD Scale %	-QCD Scale %	±(PDF+α_s) %	±PDF %	±α_s %
pp→ZH	0.8839	+3.8%	-3.1%	±1.6%	±1.3%	±0.9%
qq/qg→ZH, gg→HZ+qqbar (all but gg→ZH)	0.7612	+0.5%	-0.6%	±1.9%	±1.7%	±0.9%
gg→ZH	0.1227	+25.1%	-18.9%	±2.4%	±1.8%	±1.6%

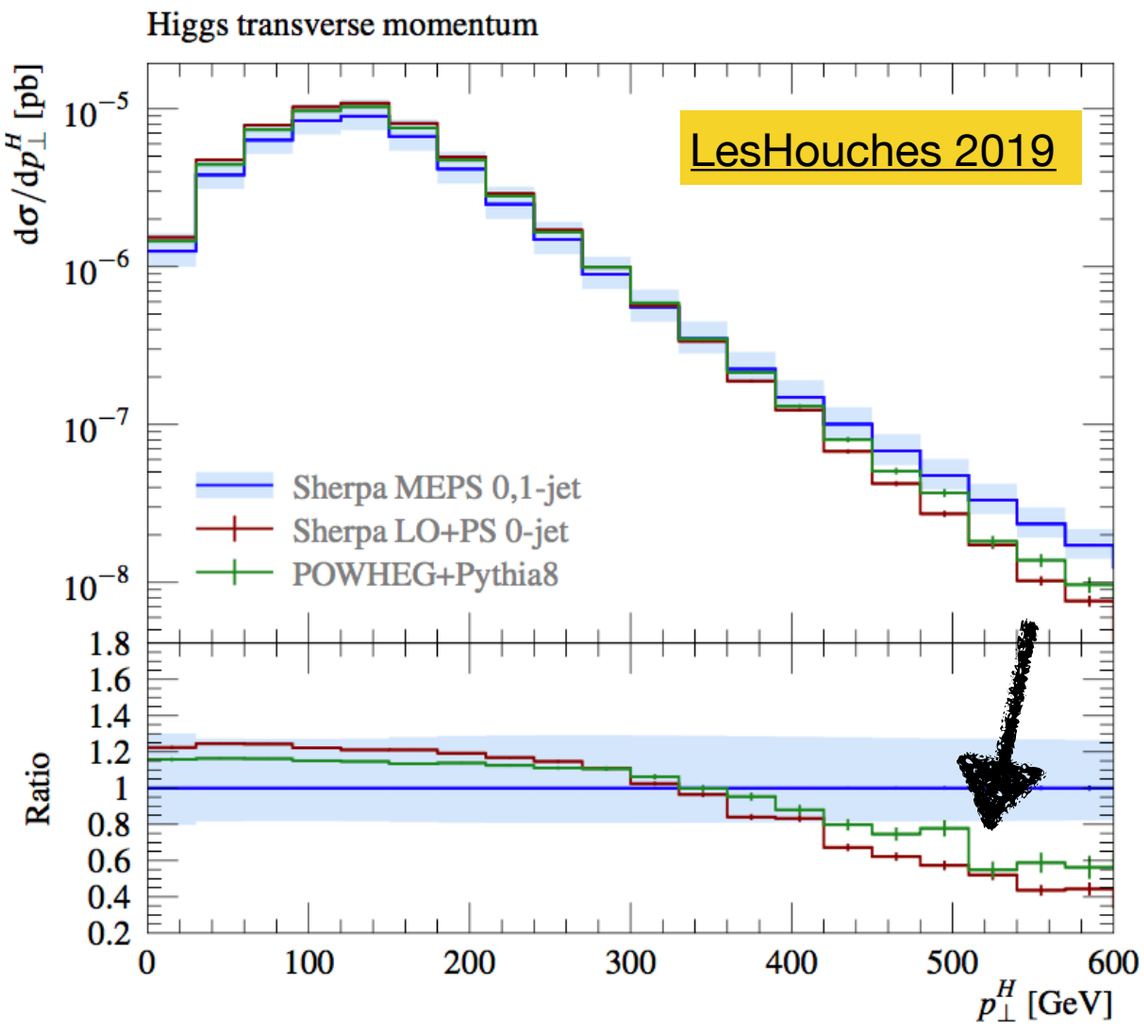
CERN YR4

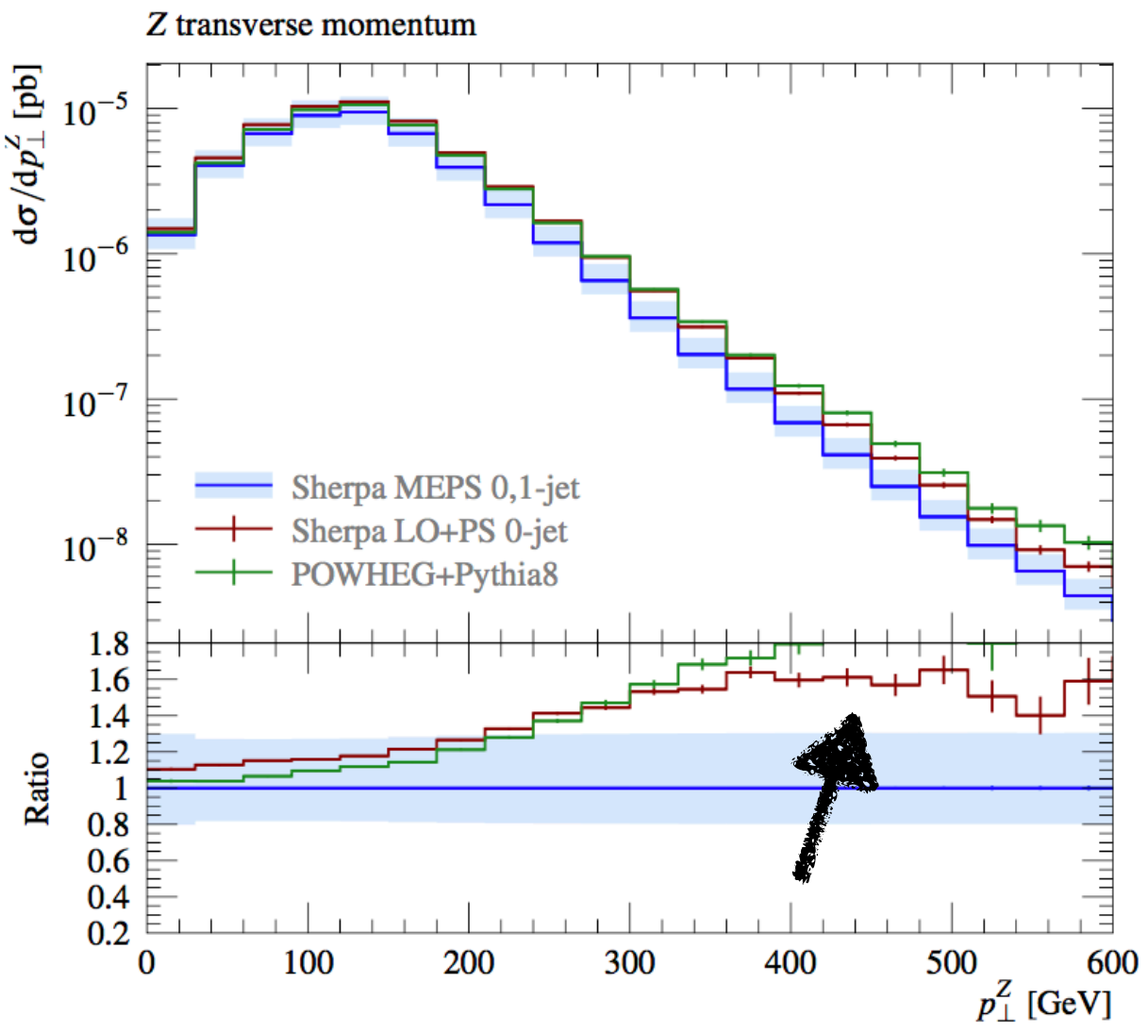
Signal modeling of ggZH process - hard scattering

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

- sizeable modifications in ptH/ptV spectra



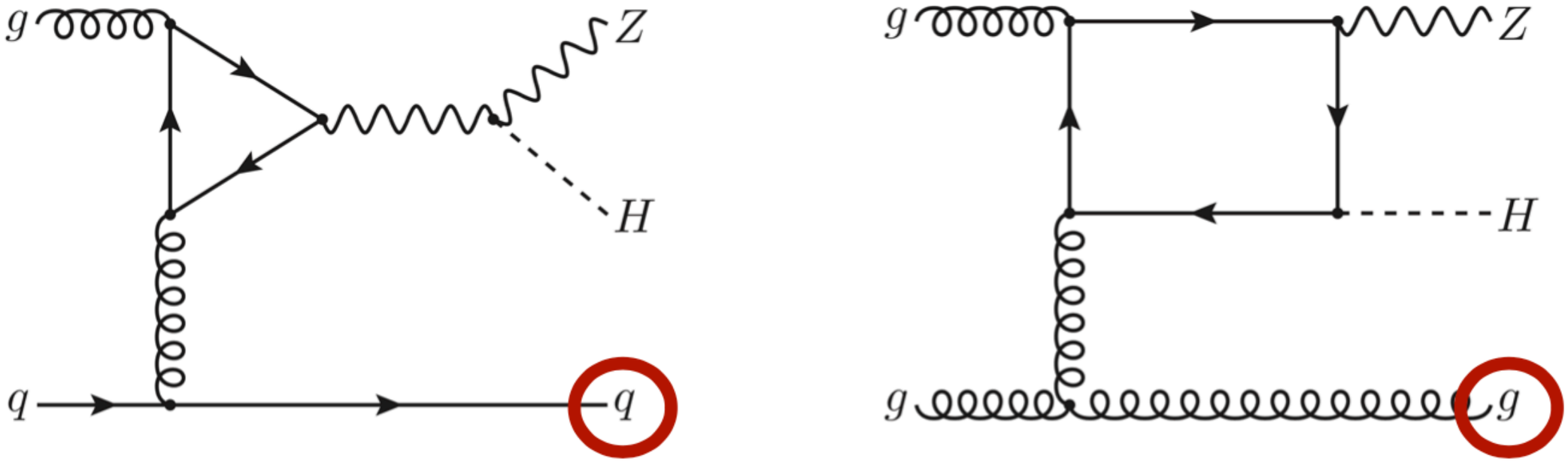




➡ Increase of QCD scale uncertainties in 2→3 processes wrt Powheg+Pythia 2→2 (23% →38% on total ggZH cross-section)

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 MG 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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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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Signal modeling of branching ratios and Hbb decays

ATLAS 2007.02873

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m_{bb} from PDF+α_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

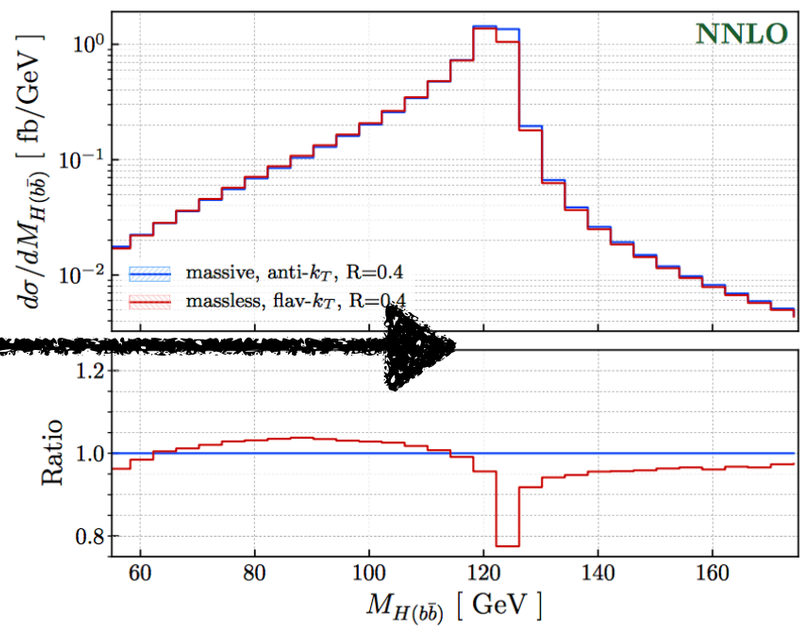
Decay in Hbb known at N3LO with inclusion of effects due to finite bottom-quark mass in NNLO predictions

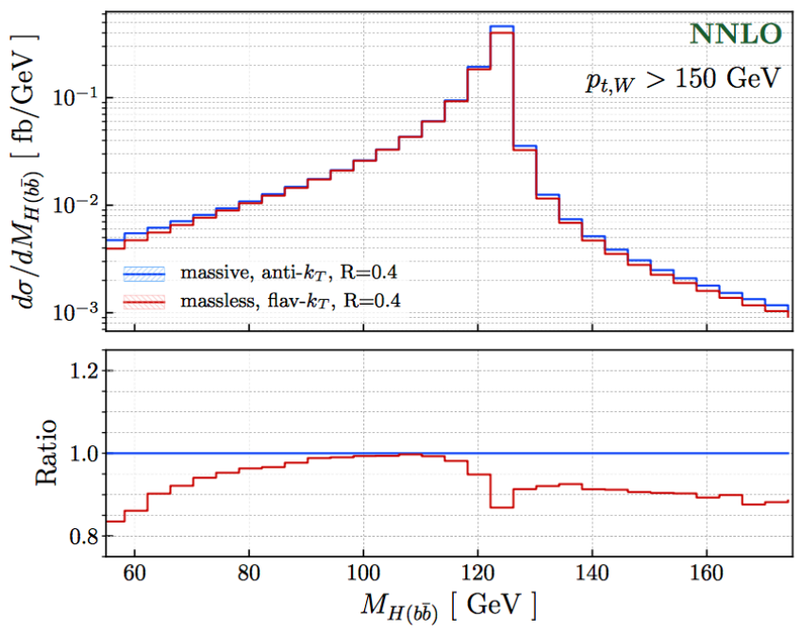
W. Astill et al. A. Behring et al

R. Mondini, C. Williams et al

NEW

- Finite b-quark mass calculation on NNLO has large impact on m(bb) lineshape modelling especially in high pt
- Interesting to check if the effect is covered by PS uncertainties
- PS comparisons on m(bb) lineshape discussed here [A. Behring et al.]





Background modeling

V+jets modeling

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Source of uncertainty		σ_μ 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
tt		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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➡ 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/ choice of systematics variations can impact the measurement significantly

V+jets modeling (2)

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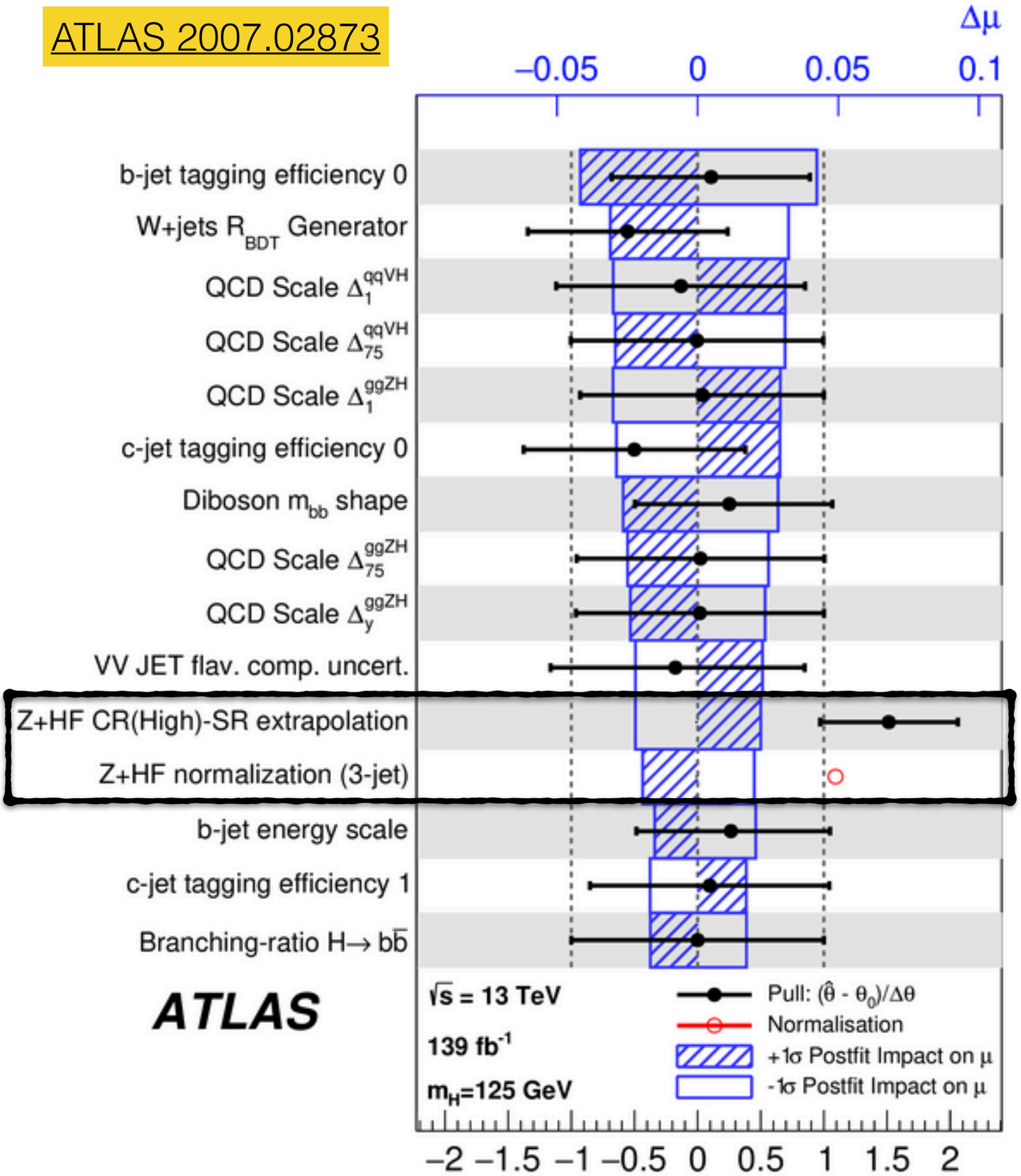


➡ Different strategies in ATLAS and CMS on V+jets

- modelling of MC prediction
- associated modelling uncertainties
- phase-space for rate-parameter constraints (backup material)

	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)

➡ 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
- recent article on predictions for Z+b-jets at $O(\alpha_S^3)$ [R. Gauld et al.]

ATLAS 2007.02873

Process and Category	Normalisation factor
$t\bar{t}$ 2-jet	0.98 ± 0.09
$t\bar{t}$ 3-jet	0.93 ± 0.06
W + HF 2-jet	1.06 ± 0.11
W + HF 3-jet	1.15 ± 0.09
Z + HF 2-jet, $75 < p_{\mathrm{T}}^{V} < 150$ GeV	1.28 ± 0.08
Z + HF 3-jet, $75 < p_{\mathrm{T}}^{V} < 150$ GeV	1.17 ± 0.05
Z + HF 2-jet, 150 GeV $< p_{\mathrm{T}}^{V}$	1.16 ± 0.07
Z + HF 3-jet, 150 GeV $< p_{\mathrm{T}}^{V}$	1.09 ± 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 ± 0.07	1.04 ± 0.07		
W + b	2.09 ± 0.16	2.09 ± 0.16		
W + $b\bar{b}$	1.74 ± 0.21	1.74 ± 0.21	–	–
Z + udscg	0.95 ± 0.09	–	0.89 ± 0.06	0.81 ± 0.05
Z + b	1.02 ± 0.17	–	0.94 ± 0.12	1.17 ± 0.10
Z + $b\bar{b}$	1.20 ± 0.11	–	0.81 ± 0.07	0.88 ± 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 measurements with full Run 2 dataset

- comparisons of analysis strategies and especially on the treatment of the V+jets background modelling of outmost importance
- plan to follow-up with dedicated discussions in next VH WG1 sub-group meetings

Backup slides

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

➡ ttbar and single-top modelling achieved with different approaches in ATLAS and CMS

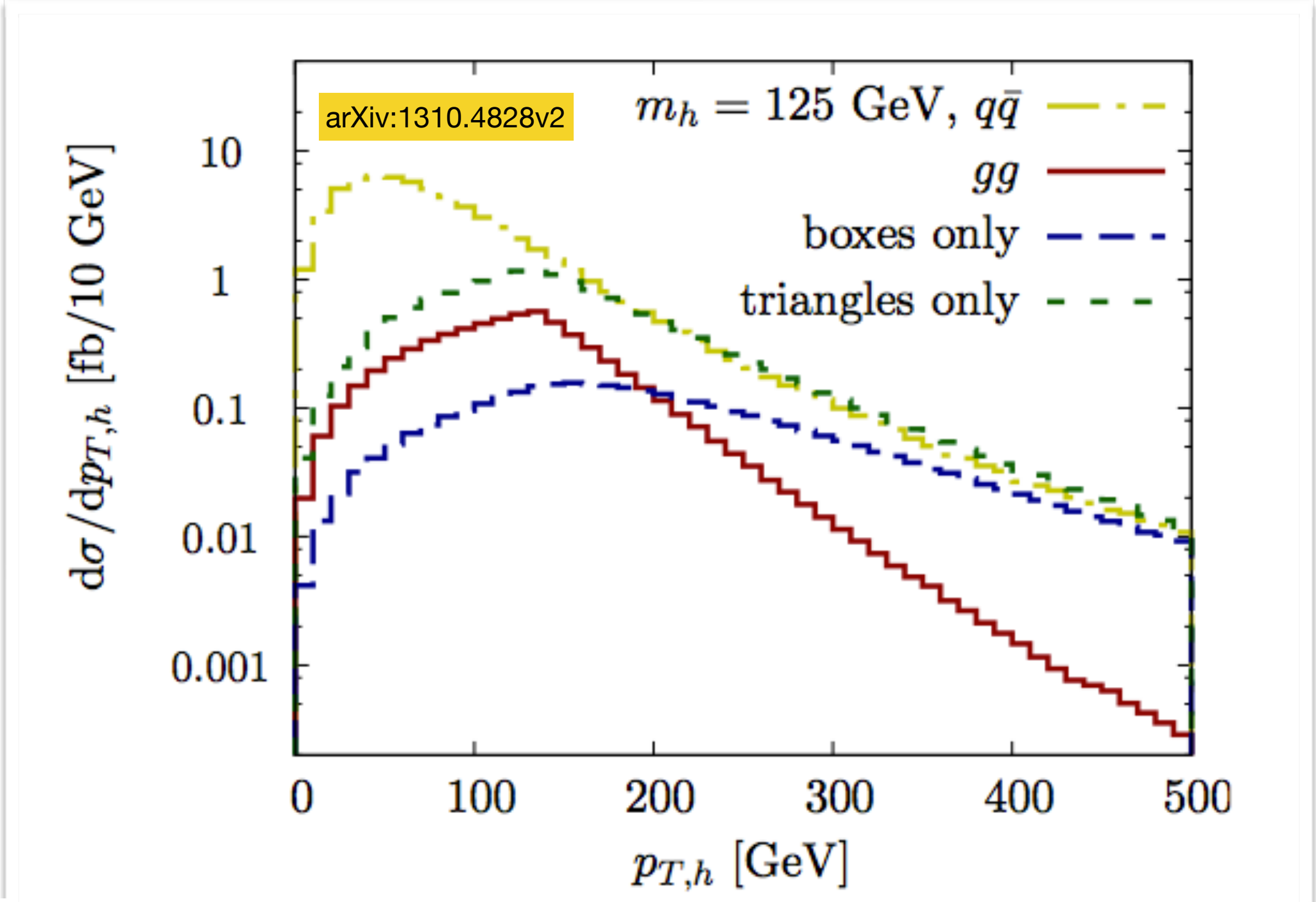
- CMS: MC-based analysis (PP8) and dedicated tt-enriched control regions to constrain shape and normalisation with data
- ATLAS: MC-based measurement with addition of data-driven techniques in 2lep channel

- Studies by ATLAS on 0/1lep and boosted Hbb regarding tt ptV/ptH spectrum using PP8 [link, boosted Hbb results]
- PP8 Wt DS found to provide better agreement with data
- no problematic issues in MC predictions - post-fit process rate parameters for ttbar processes largely constrained and close to unity due to excellent purity of tt-enriched regions

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)



V+jets modeling (3)

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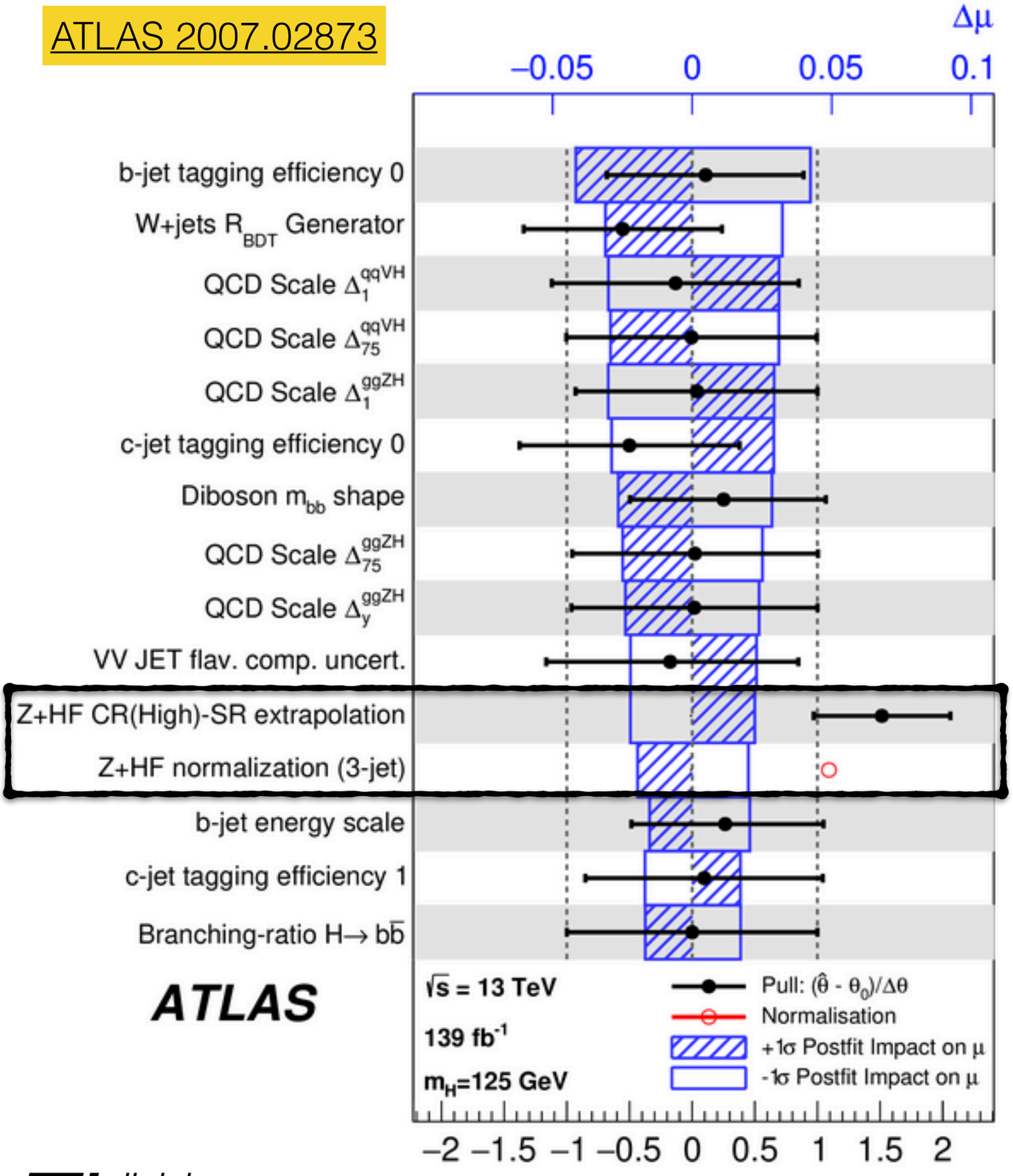

- Different strategies in ATLAS and CMS on V+jets
  - modelling of MC prediction
  - associated modelling uncertainties
  - phase-space for rate-parameter constraints

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!

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