Observation of H→bb decays and VH production with the ATLAS detector

LIU Kun (LPNHE-Paris)
on behalf of the ATLAS Collaboration

LHC Higgs WG1 VH subgroup meeting
15th Nov., 2018

Outline

Introduction and analysis strategy

- physics motivation
- analysis strategy
- event selection and observables

Signal and background modelling

- MC configurations
- signal modelling
- background modelling

Results

- VH, H→bb result
- H→bb combination result
- VH production combination result

Summary

Introduction

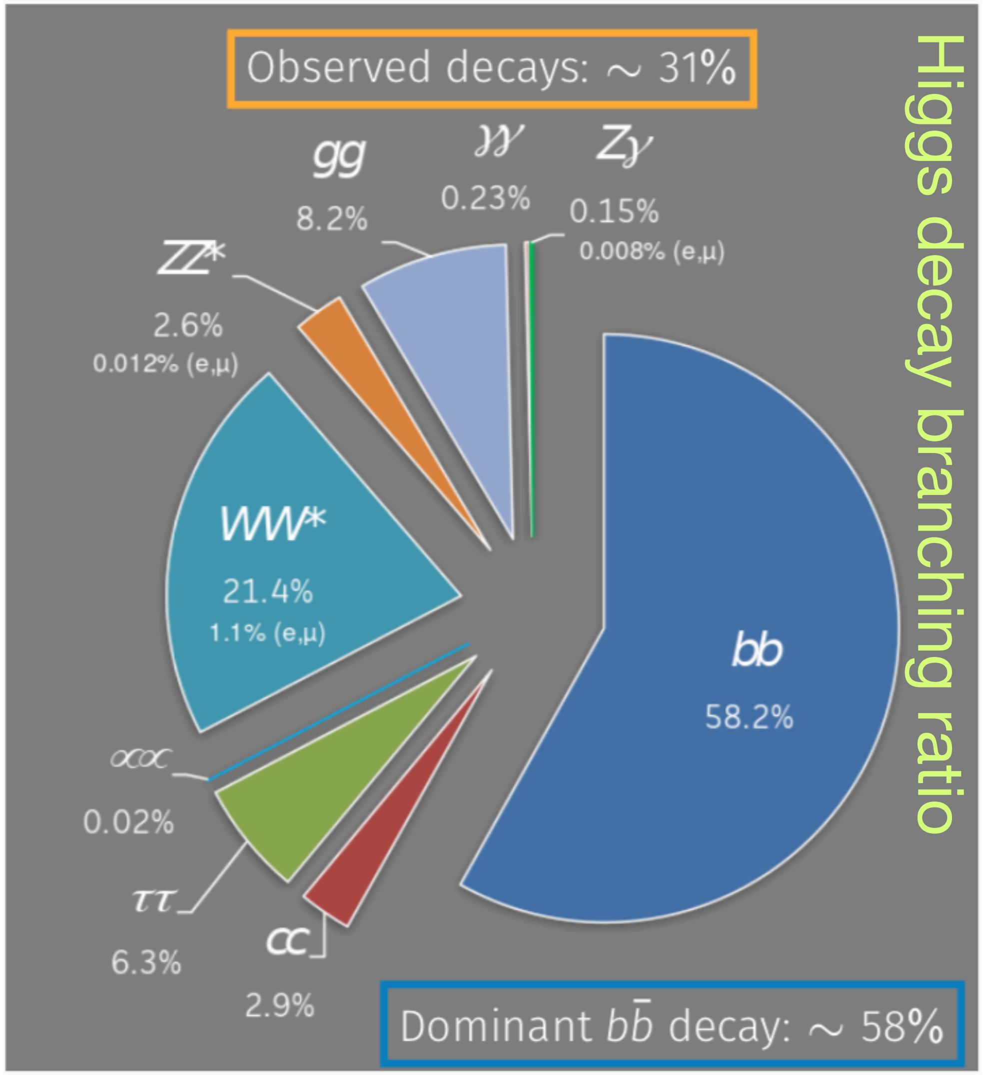
H→bb decays has the largest Higgs BR ∽ 58%, which has been observed until recently (6 years after Higgs discovery).

H→bb decays allows a direct access to Higgs coupling to bottom-quark at tree level.

VH, H→bb channel has the biggest discovery potential for both H→bb decays and VH production.

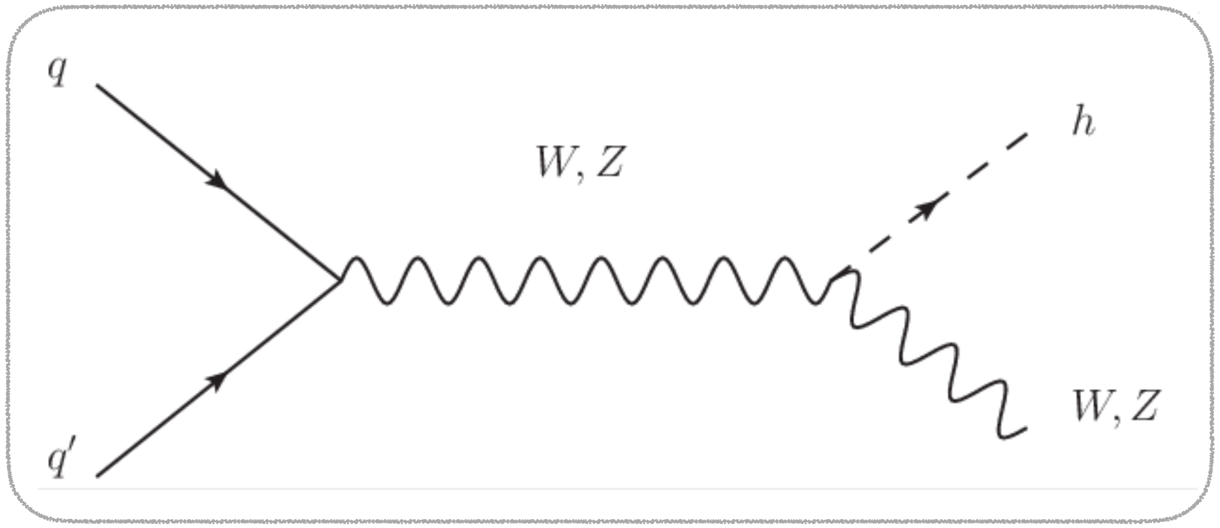
Leptonic decay of the vector boson enables

- ✓ efficient triggering
- ✓ a significant reduction of multi-jet background.



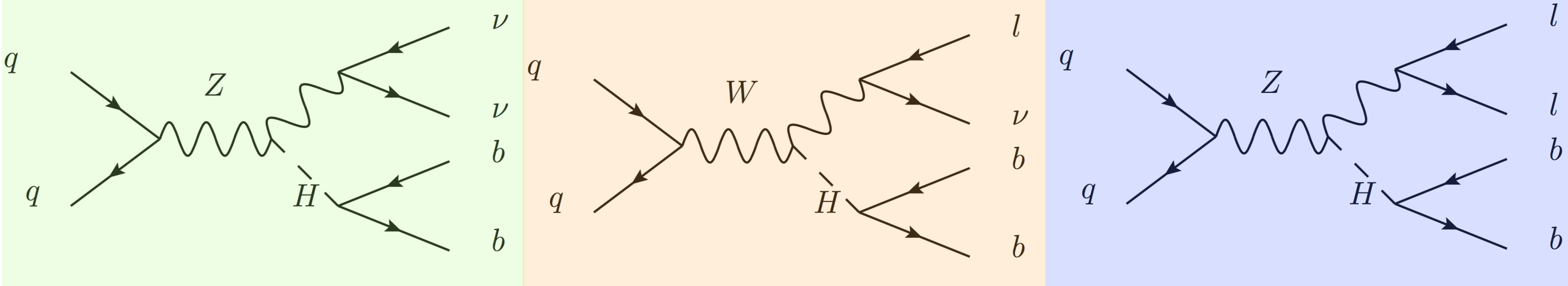
Analysis strategy :

- VH(H→bb) MVA(BDT) analysis as default
- cross check 1: VZ(Z→bb) MVA analysis
- cross check 2: VH m_{bb} fit analysis (cut-based selection).



Event selection and categorisation

There are three analysis channels according to number of charged leptons:



Selection	0-lepton	1-lepton		2-lepton
		e sub-channel	μ sub-channel	
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton
Leptons	0 *loose* leptons with $p_{\mathrm{T}} > 7$ GeV	1 *tight* electron $p_{\mathrm{T}} > 27$ GeV	1 *tight* muon $p_{\mathrm{T}} > 25$ GeV	2 *loose* leptons with $p_{\mathrm{T}} > 7$ GeV ≥ 1 lepton with $p_{\mathrm{T}} > 27$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–		81 GeV $< m_{\ell\ell} <$ 101 GeV
Jets	Exactly 2 / Exactly 3 jets			Exactly 2 / ≥ 3 jets
Jet p_{T}	> 20 GeV for $\lvert\eta\rvert < 2.5$ > 30 GeV for $2.5 < \lvert\eta\rvert < 4.5$			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_{T}	> 45 GeV			
H_{T}	> 120 GeV (2 jets), >150 GeV (3 jets)	–		–
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{\mathrm{jets}})]$	$> 20^{\circ}$ (2 jets), $> 30^{\circ}$ (3 jets)	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{bb})$	$> 120^{\circ}$	–		–
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140^{\circ}$	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	$< 90^{\circ}$	–		–
p_{T}^{V} regions	> 150 GeV			75 GeV $< p_{\mathrm{T}}^{V} <$ 150 GeV, $>$ 150 GeV
Signal regions	–	$m_{bb} \geq 75$ GeV or $m_{\mathrm{top}} \leq 225$ GeV		Same-flavour leptons Opposite-sign charges ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{\mathrm{top}} > 225$ GeV		Different-flavour leptons Opposite-sign charges

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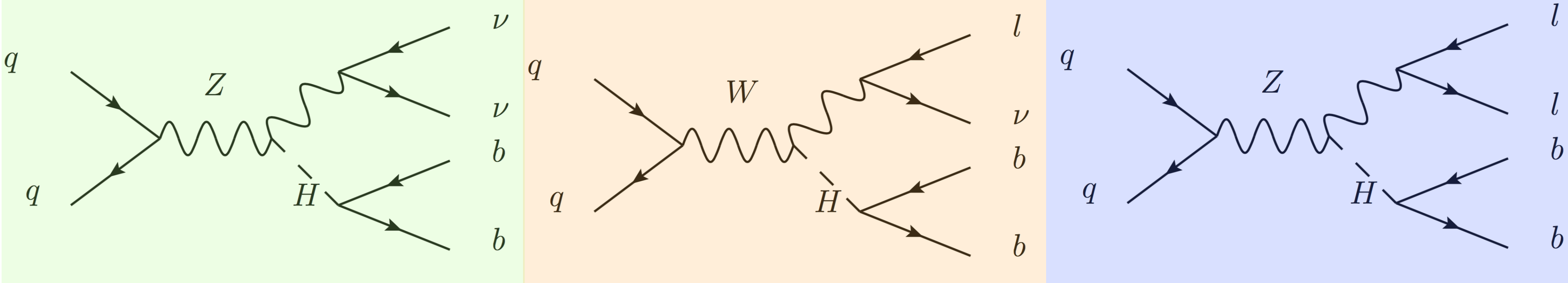


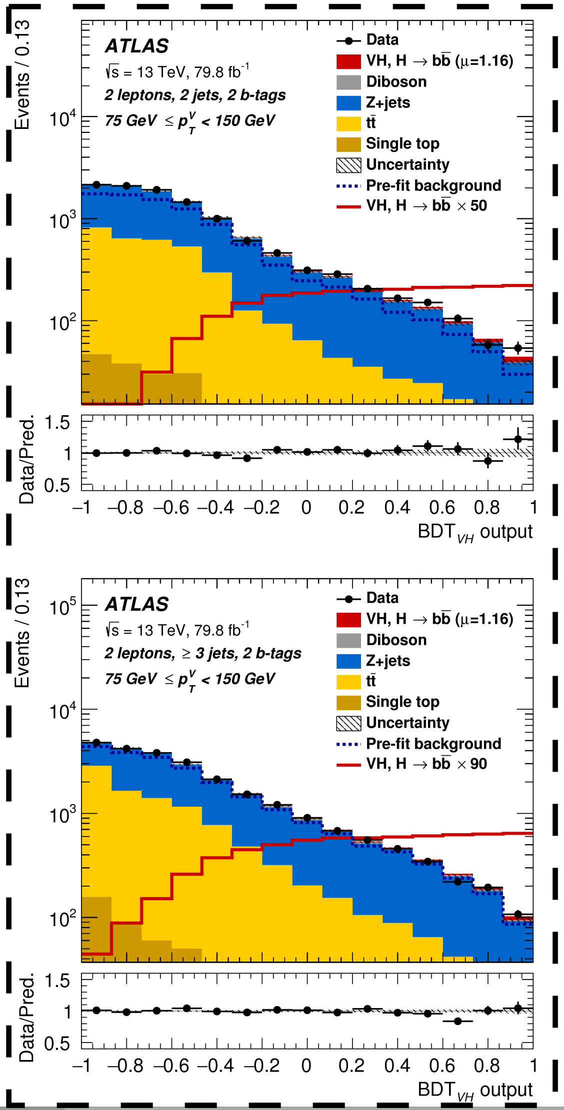
Selection	0-lepton	1-lepton e sub-channel	 μ sub-channel	2-lepton
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton
Leptons				
$E_{\mathrm{T}}^{\mathrm{miss}}$				
$m_{\ell\ell}$				
Jets				
Jet p_{T}				
b-jets				
Leading b-tagged jet p				
H_{T}				
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{\mathrm{jets}})]$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{bb})$	$> 120^\circ$	–		–
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140^\circ$	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	$< 90^\circ$	–		–
p_{T}^{V} regions	> 150 GeV			75 GeV $< p_{\mathrm{T}}^{V} <$ 150 GeV, $>$ 150 GeV
Signal regions	–	$m_{bb} \geq 75$ GeV or $m_{\mathrm{top}} \leq 225$ GeV		Same-flavour leptons Opposite-sign charges ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{\mathrm{top}} > 225$ GeV		Different-flavour leptons Opposite-sign charges

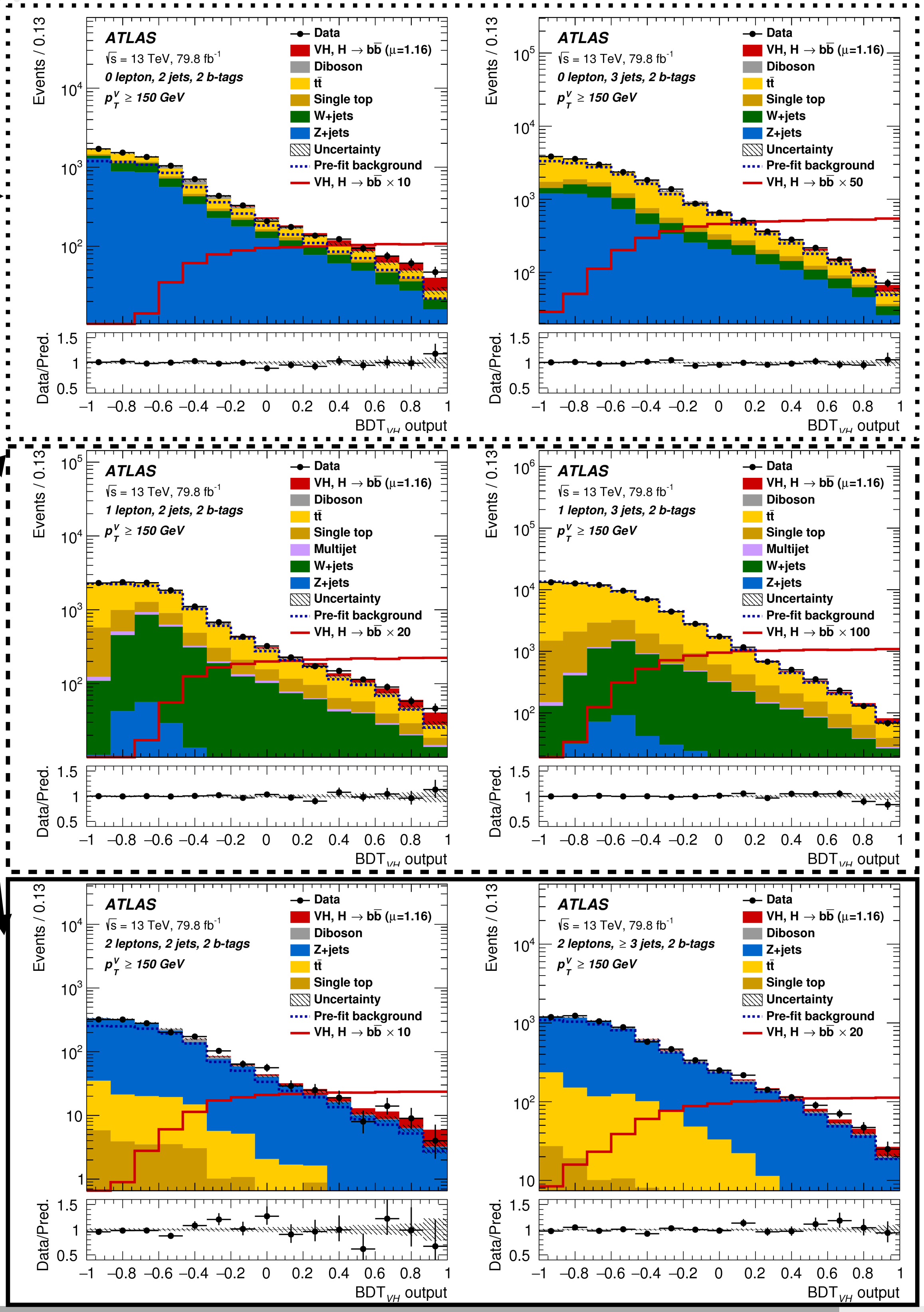
- ➡ harmonising as much as possible the selection among channels.
- ➡ Requiring two b-tagged jets with 70% b-tagging WP (0.3% efficiency for light-jet and 12.5% efficiency for c-jet) ensures non V+bx background to be negligible.

Analysis regions and discriminants

Channel	SR/CR	Categories			
		$75\text{ GeV} < p_T^V < 150\text{ GeV}$		$p_T^V > 150\text{ GeV}$	
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	-	-	BDT	BDT
1-lepton	SR	-	-	BDT	BDT
2-lepton	SR	BDT	BDT	BDT	BDT
1-lepton	$W+\text{HF}$ CR	-	-	Yield	Yield
2-lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield	m_{bb}

- ●— **Data**
- 🟥 **VH, H → $b\bar{b}$ (μ=1.16)**
- ⬜ **Diboson**
- 🟨 **$t\bar{t}$**
- 🟧 **Single top**
- 🟪 **Multijet**
- 🟩 **W+jets**
- 🟦 **Z+jets**
- ▨ **Uncertainty**
- ┈ **Pre-fit background**
- — **VH, H → $b\bar{b}$ × 100**





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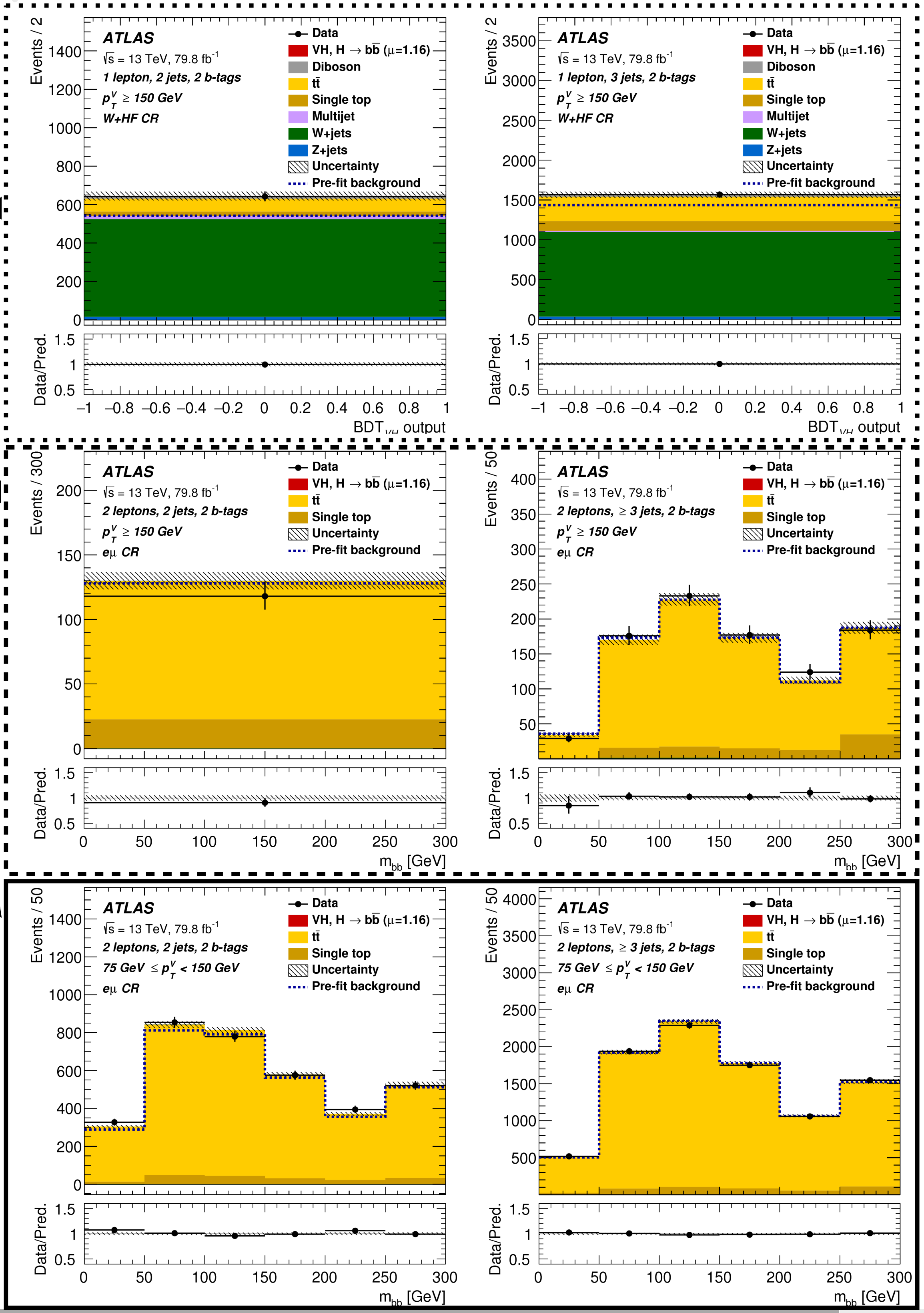
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	-	-	BDT	BDT
1-lepton	SR	-	-	BDT	BDT
2-lepton	SR	BDT	BDT	BDT	BDT
1-lepton	W + HF CR	-	-	Yield	Yield
2-lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield	m_{bb}

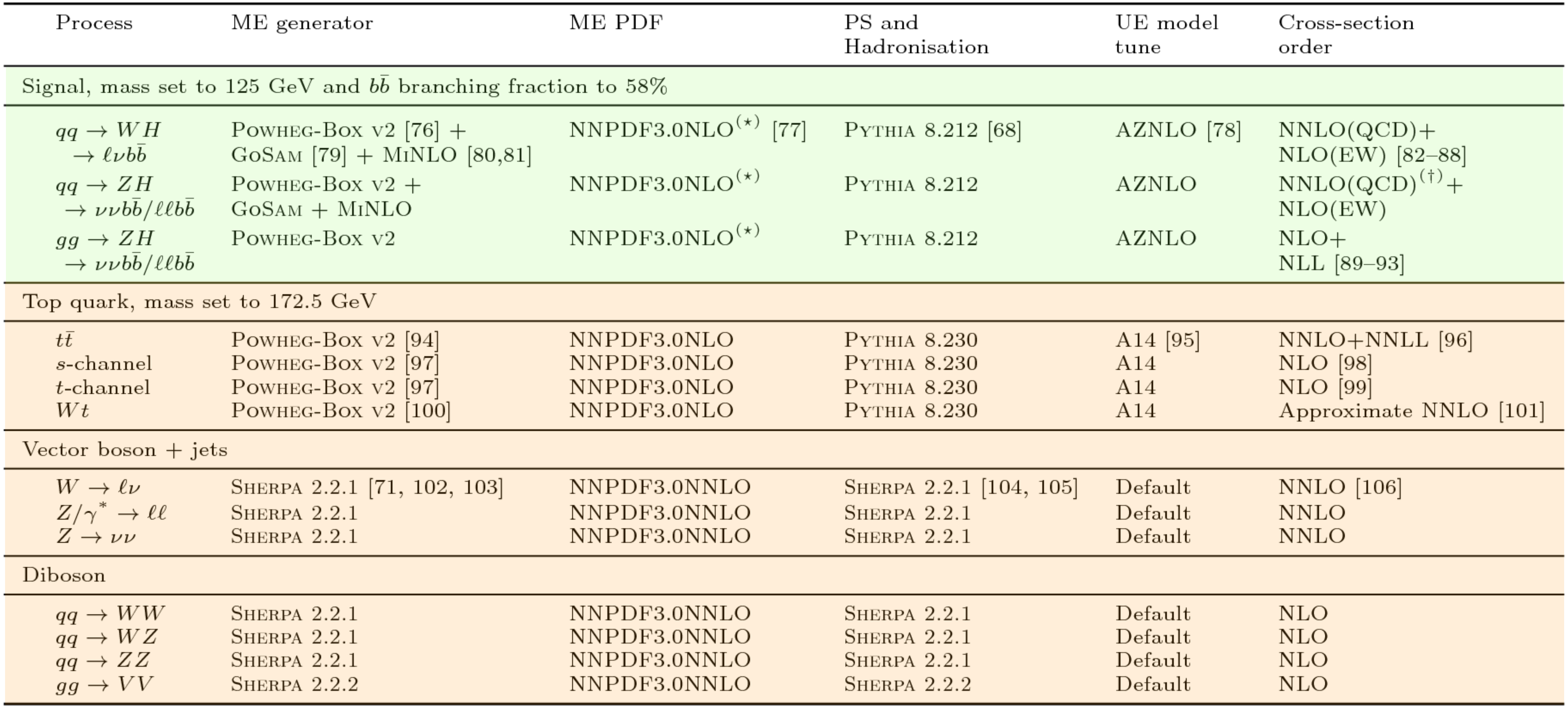


Choice of Control Regions:

- ✦ **in 2L**: close to 0 normalisation and shape extrapolation uncertainties between SR and CR
- ✦ **in 1L**: m_{top} is reconstructed as the invariant mass of the lepton, the reconstructed neutrino and the b-tagged jet yields the lowest mass value.

All regions are fitted simultaneously to extract parameters of interest.

Signal and background MC configurations



Process	ME generator	ME PDF	PS and Hadronisation	UE model tune	Cross-section order
Signal, mass set to 125 GeV and $b\bar{b}$ branching fraction to 58%					
$qq \to WH \to \ell\nu b\bar{b}$	Powheg-Box v2 [76] + GoSam [79] + MiNLO [80,81]	NNPDF3.0NLO$^{(\star)}$ [77]	Pythia 8.212 [68]	AZNLO [78]	NNLO(QCD)+ NLO(EW) [82–88]
$qq \to ZH \to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	Powheg-Box v2 + GoSam + MiNLO	NNPDF3.0NLO$^{(\star)}$	Pythia 8.212	AZNLO	NNLO(QCD)$^{(\dagger)}$+ NLO(EW)
$gg \to ZH \to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	Powheg-Box v2	NNPDF3.0NLO$^{(\star)}$	Pythia 8.212	AZNLO	NLO+ NLL [89–93]
Top quark, mass set to 172.5 GeV					
$t\bar{t}$	Powheg-Box v2 [94]	NNPDF3.0NLO	Pythia 8.230	A14 [95]	NNLO+NNLL [96]
s-channel	Powheg-Box v2 [97]	NNPDF3.0NLO	Pythia 8.230	A14	NLO [98]
t-channel	Powheg-Box v2 [97]	NNPDF3.0NLO	Pythia 8.230	A14	NLO [99]
Wt	Powheg-Box v2 [100]	NNPDF3.0NLO	Pythia 8.230	A14	Approximate NNLO [101]
Vector boson + jets					
$W \to \ell\nu$	Sherpa 2.2.1 [71, 102, 103]	NNPDF3.0NNLO	Sherpa 2.2.1 [104, 105]	Default	NNLO [106]
$Z/\gamma^* \to \ell\ell$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
$Z \to \nu\nu$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
Diboson					
$qq \to WW$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
$qq \to WZ$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
$qq \to ZZ$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
$gg \to VV$	Sherpa 2.2.2	NNPDF3.0NNLO	Sherpa 2.2.2	Default	NLO

MC simulated events are used to model the SM backgrounds and VH, H➞bb signal processes

- ➡ all processes are normalised using most accurate theoretical cross-section predictions
- ➡ ttbar is generated at NLO accuracy; V+ 0/1/2 (3/4) jets are generated at NLO (LO) accuracy.

Alternative samples for systematics are listed in backup slides.

Signal and background modelling systematics

Three areas of modelling systematics for the simulated samples

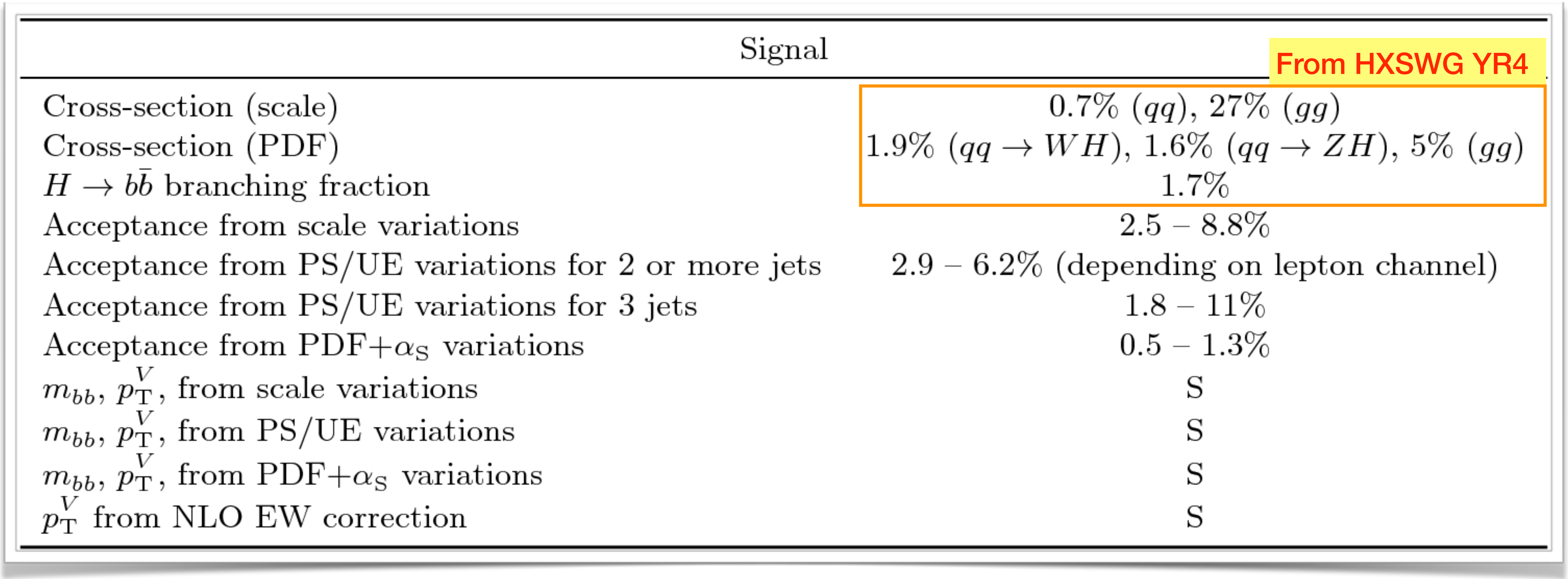
- overall normalisation and associated uncertainty: currently most accurate calculations [table]
- acceptance/extrapolation between SR and CR: changing generator or altering generator parameters
- shape systematics parametrised independently as a function of m_{bb} and pTV: leading variables in BDT.

Data provides constraint on the normalisation of main backgrounds via the global likelihood fit.

Process	Normalisation factor	
$t\bar{t}$ 0- and 1-lepton	0.98 ± 0.08	constrain in 0/1-lep SR
$t\bar{t}$ 2-lepton 2-jet	1.06 ± 0.09	constrain in ttbar CR
$t\bar{t}$ 2-lepton 3-jet	0.95 ± 0.06	
$W +$ HF 2-jet	1.19 ± 0.12	constrain in W+HF CR
$W +$ HF 3-jet	1.05 ± 0.12	
$Z +$ HF 2-jet	1.37 ± 0.11	constrain in 0/2-lep SR
$Z +$ HF 3-jet	1.09 ± 0.09	

HF: heavy-flavour includes bb, bc, bl and cc components.

Signal modelling uncertainties



From HXSWG YR4

Signal	
Cross-section (scale)	0.7% (qq), 27% (gg)
Cross-section (PDF)	1.9% ($qq \to WH$), 1.6% ($qq \to ZH$), 5% (gg)
$H \to b\bar{b}$ branching fraction	1.7%
Acceptance from scale variations	2.5 – 8.8%
Acceptance from PS/UE variations for 2 or more jets	2.9 – 6.2% (depending on lepton channel)
Acceptance from PS/UE variations for 3 jets	1.8 – 11%
Acceptance from PDF+α_S variations	0.5 – 1.3%
m_{bb}, p_T^V, from scale variations	S
m_{bb}, p_T^V, from PS/UE variations	S
m_{bb}, p_T^V, from PDF+α_S variations	S
p_T^V from NLO EW correction	S

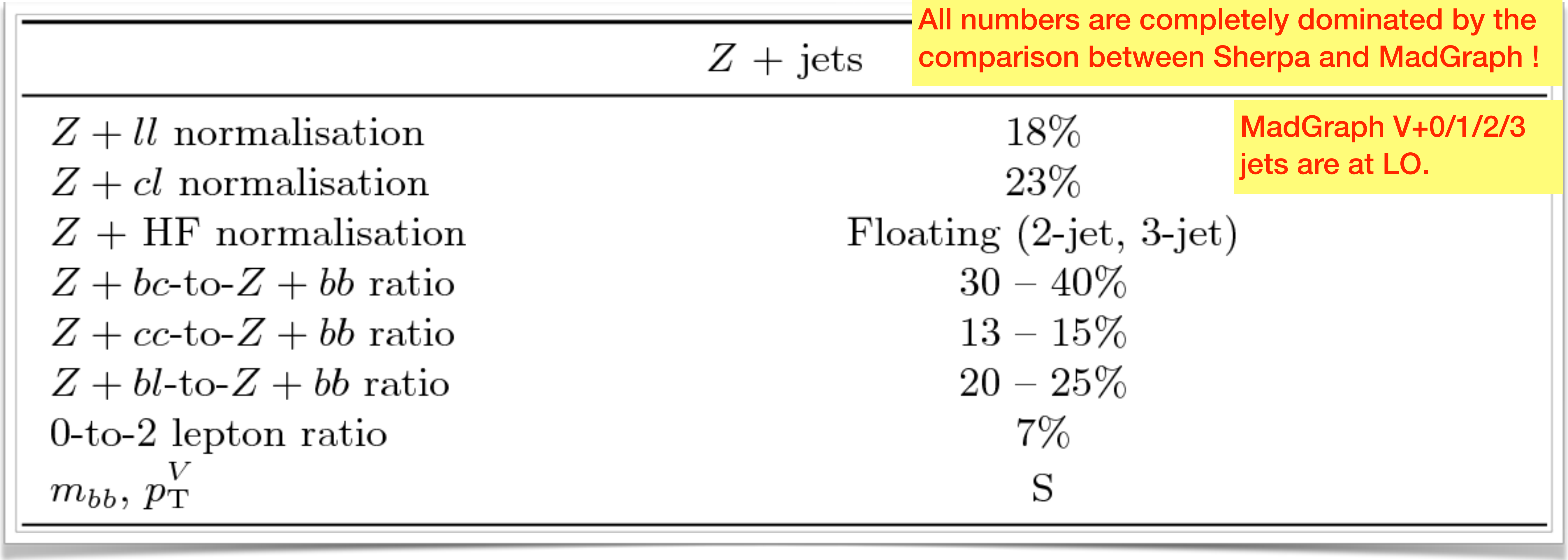
Updates w.r.t VHbb-Evidence analysis with 36.1 fb^{-1}

- larger number of events from alternative samples
- more recent parton shower uncertainty

➡ reduce the parton shower and underlying event uncertainties.

To account for higher order EW effects on overall VH XS, we use as NLO EW uncertainty as function of pTV: max{NLOEW^2, 1%, Delta_gamma}.

Background modelling uncertainties - Z+jets



	Z + jets
$Z+ll$ normalisation	18%
$Z+cl$ normalisation	23%
Z + HF normalisation	Floating (2-jet, 3-jet)
$Z+bc$-to-$Z+bb$ ratio	30 – 40%
$Z+cc$-to-$Z+bb$ ratio	13 – 15%
$Z+bl$-to-$Z+bb$ ratio	20 – 25%
0-to-2 lepton ratio	7%
m_{bb}, p_{T}^{V}	S

All numbers are completely dominated by the comparison between Sherpa and MadGraph !

MadGraph V+0/1/2/3 jets are at LO.

V+ll and V+cl components constitute < 1% of total background → only normalisation uncertainty.

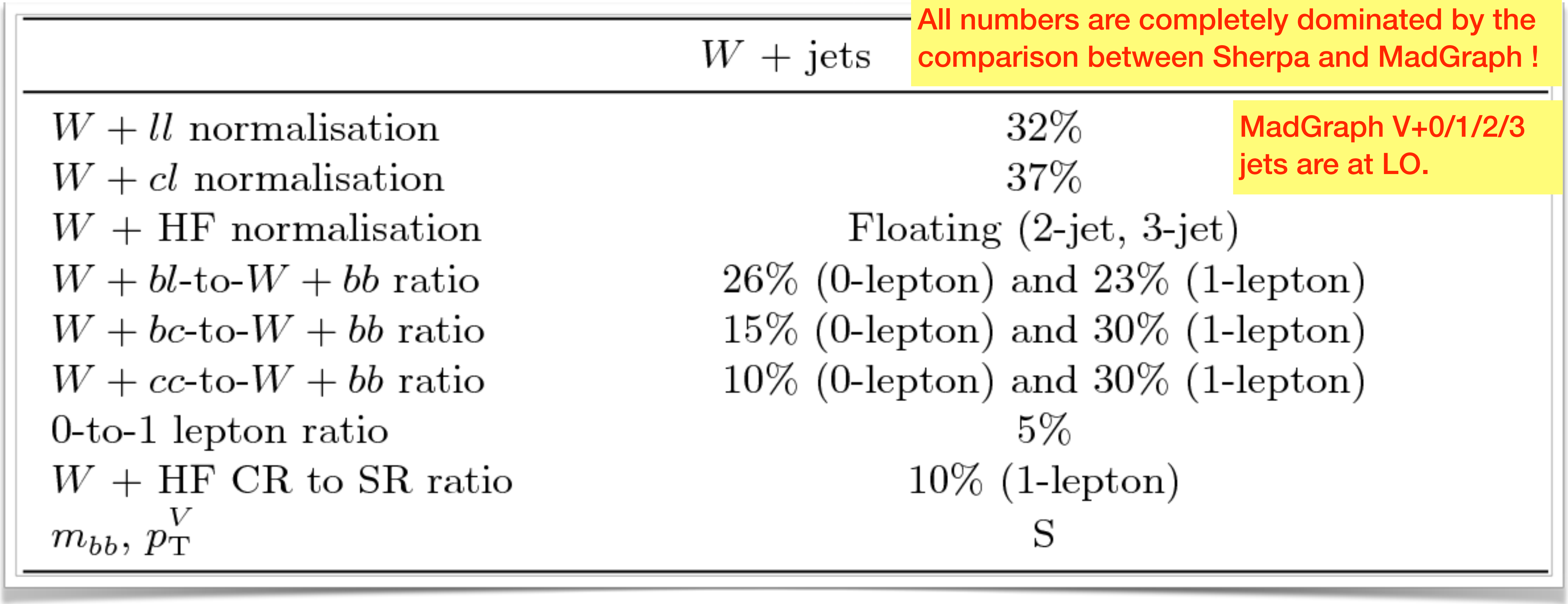
Acceptance uncertainties for the relative normalisations sharing a common floating parameter:

- V+HF: bc/cc/bl to bb yield ratio → little impact on the final sensitivity
- 0-lepton to 2-lepton channel yield ratio.

mbb, pTV shapes are extracted from data/mc in sidebands.

Process	Normalisation factor
Z + HF 2-jet	1.37 ± 0.11
Z + HF 3-jet	1.09 ± 0.09

Background modelling uncertainties - W+jets



	W + jets
$W + ll$ normalisation	32%
$W + cl$ normalisation	37%
W + HF normalisation	Floating (2-jet, 3-jet)
$W + bl$-to-$W + bb$ ratio	26% (0-lepton) and 23% (1-lepton)
$W + bc$-to-$W + bb$ ratio	15% (0-lepton) and 30% (1-lepton)
$W + cc$-to-$W + bb$ ratio	10% (0-lepton) and 30% (1-lepton)
0-to-1 lepton ratio	5%
W + HF CR to SR ratio	10% (1-lepton)
m_{bb}, p_{T}^{V}	S

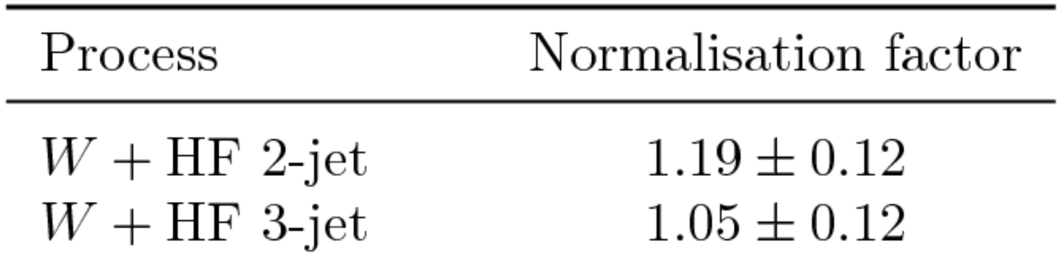
All numbers are completely dominated by the comparison between Sherpa and MadGraph !

MadGraph V+0/1/2/3 jets are at LO.

V+ll and V+cl components constitute < 1% of total background → only normalisation uncertainty.

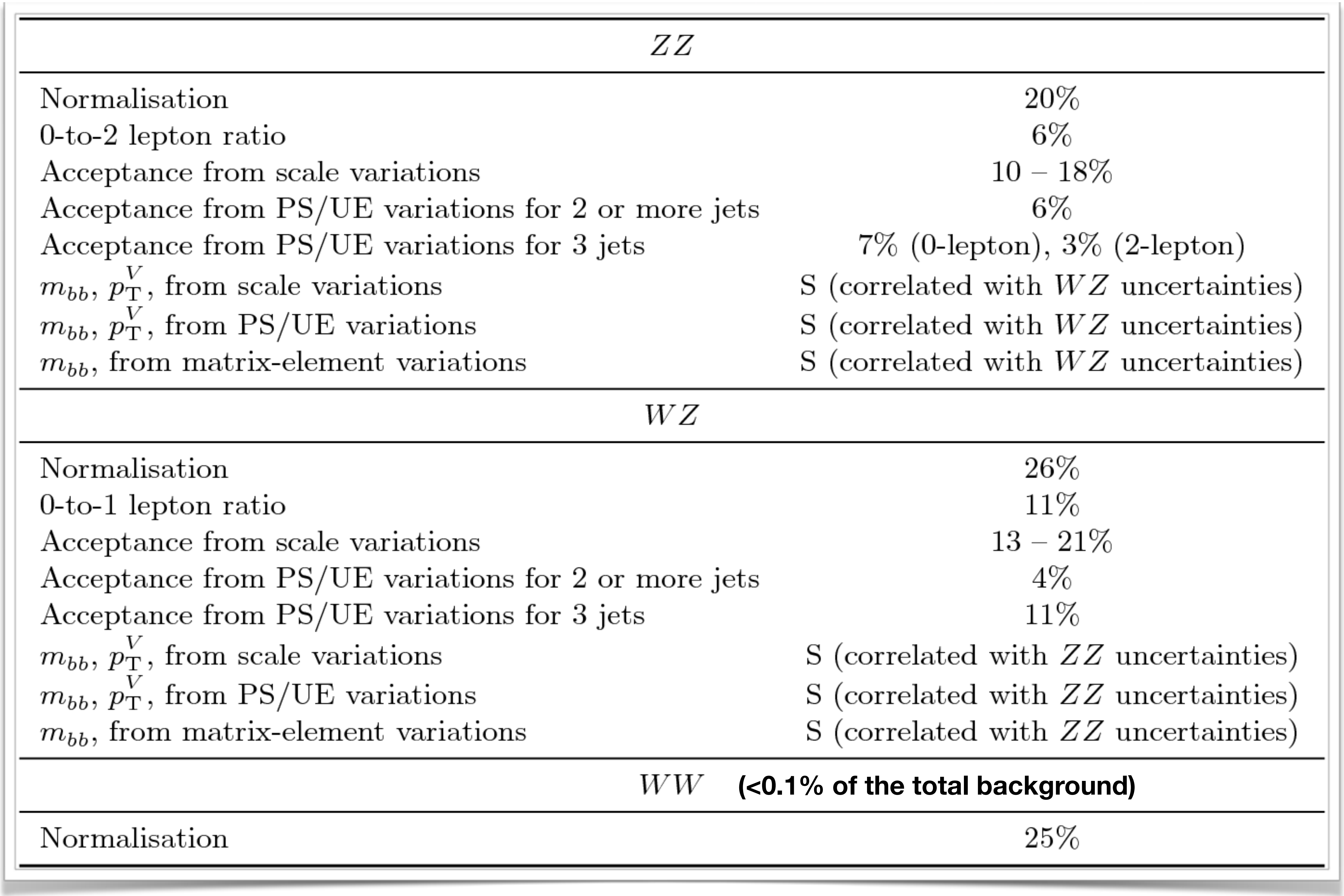
Acceptance uncertainties for the relative normalisations sharing a common floating parameter:

- V+HF: bc/cc/bl to bb yield ratio → little impact on the final sensitivity
- 0-lepton to 1-lepton channel yield ratio
- W+HF CR to SR yield ratio.



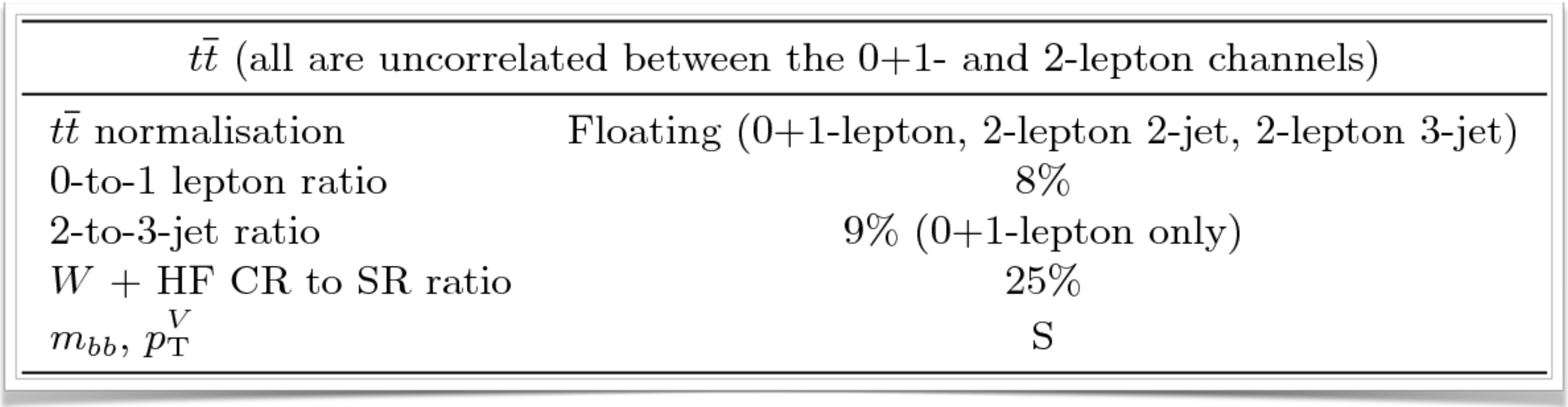
Process	Normalisation factor
W + HF 2-jet	1.19 ± 0.12
W + HF 3-jet	1.05 ± 0.12

Background modelling uncertainties - Diboson



ZZ	
Normalisation	20%
0-to-2 lepton ratio	6%
Acceptance from scale variations	10 – 18%
Acceptance from PS/UE variations for 2 or more jets	6%
Acceptance from PS/UE variations for 3 jets	7% (0-lepton), 3% (2-lepton)
m_{bb}, p_{T}^{V}, from scale variations	S (correlated with WZ uncertainties)
m_{bb}, p_{T}^{V}, from PS/UE variations	S (correlated with WZ uncertainties)
m_{bb}, from matrix-element variations	S (correlated with WZ uncertainties)
WZ	
Normalisation	26%
0-to-1 lepton ratio	11%
Acceptance from scale variations	13 – 21%
Acceptance from PS/UE variations for 2 or more jets	4%
Acceptance from PS/UE variations for 3 jets	11%
m_{bb}, p_{T}^{V}, from scale variations	S (correlated with ZZ uncertainties)
m_{bb}, p_{T}^{V}, from PS/UE variations	S (correlated with ZZ uncertainties)
m_{bb}, from matrix-element variations	S (correlated with ZZ uncertainties)
WW **(<0.1% of the total background)**	
Normalisation	25%

Background modelling uncertainties - ttbar

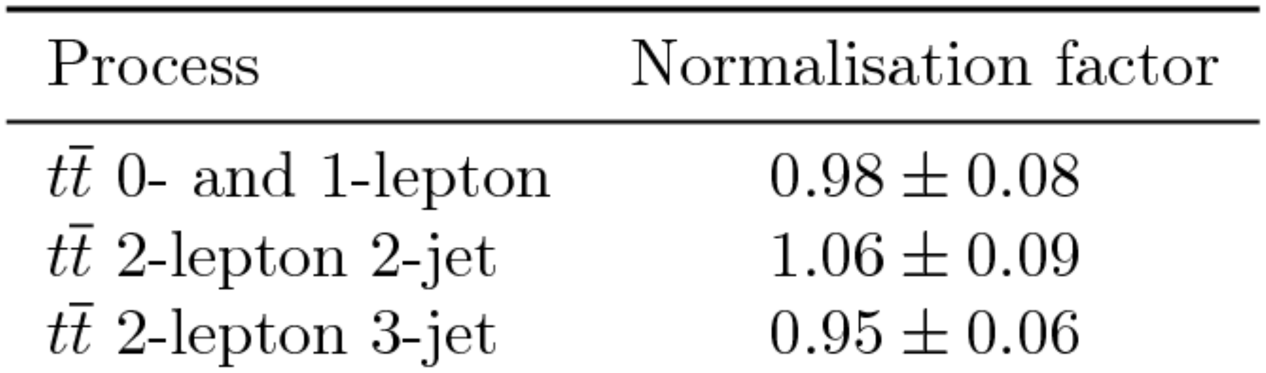


$t\bar{t}$ (all are uncorrelated between the 0+1- and 2-lepton channels)	
$t\bar{t}$ normalisation	Floating (0+1-lepton, 2-lepton 2-jet, 2-lepton 3-jet)
0-to-1 lepton ratio	8%
2-to-3-jet ratio	9% (0+1-lepton only)
W + HF CR to SR ratio	25%
m_{bb}, p_{T}^{V}	S

Independent normalisation factors are considered for 0+1-lepton, 2-lepton 2jet and 2-lepton 3-jet.

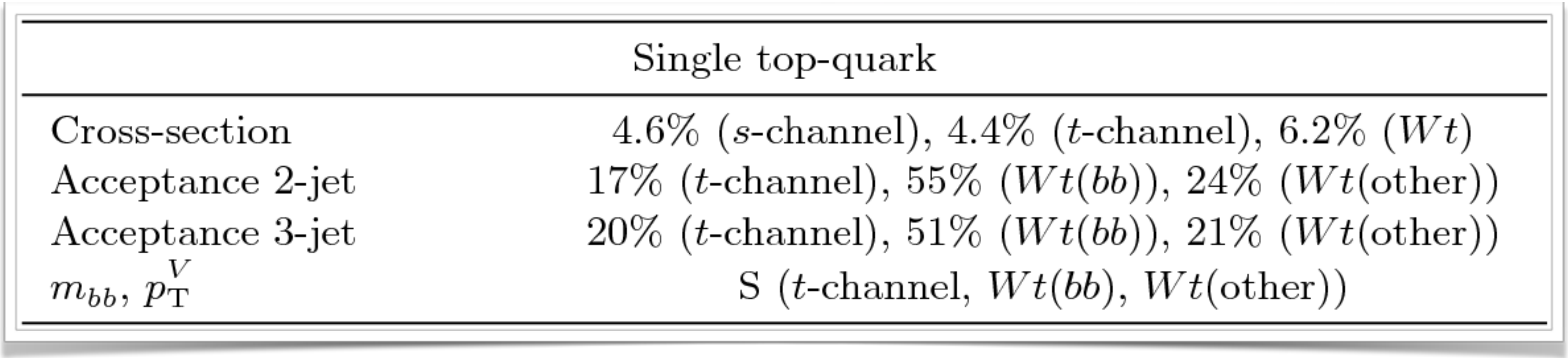
0+1-lepton channel acceptance uncertainties:

- 0-lepton to 1-lepton yield ratio
- 2-jet to 3-jet yield ratio
- W+HF CR to SR yield ratio



Process	Normalisation factor
$t\bar{t}$ 0- and 1-lepton	0.98 ± 0.08
$t\bar{t}$ 2-lepton 2-jet	1.06 ± 0.09
$t\bar{t}$ 2-lepton 3-jet	0.95 ± 0.06

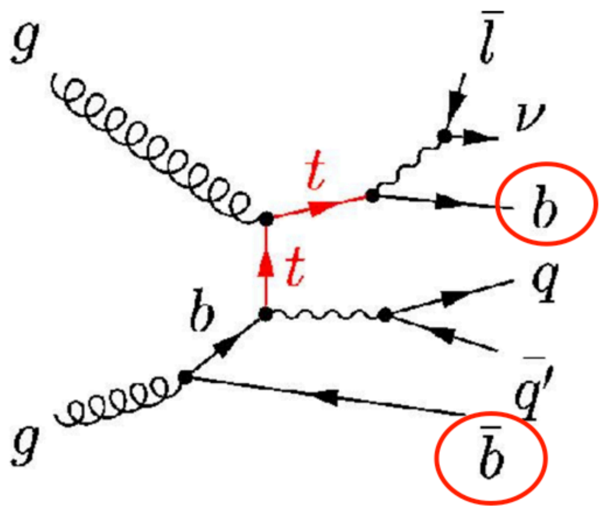
Background modelling uncertainties - single top



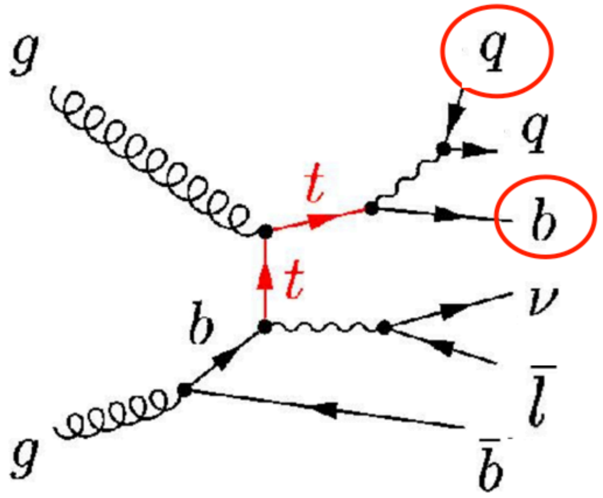
	Single top-quark
Cross-section	4.6% (s-channel), 4.4% (t-channel), 6.2% (Wt)
Acceptance 2-jet	17% (t-channel), 55% ($Wt(bb)$), 24% (Wt(other))
Acceptance 3-jet	20% (t-channel), 51% ($Wt(bb)$), 21% (Wt(other))
m_{bb}, p_{T}^{V}	S (t-channel, $Wt(bb)$, Wt(other))

Due to negligible contribution of **s-channel** only normalisation uncertainty is considered.

Wt channel: acceptance and shape systematics are considered in separated in bb or other components due to the different flavour composition/origin of b-jets being probed.



Wt (bb)



Wt (other)

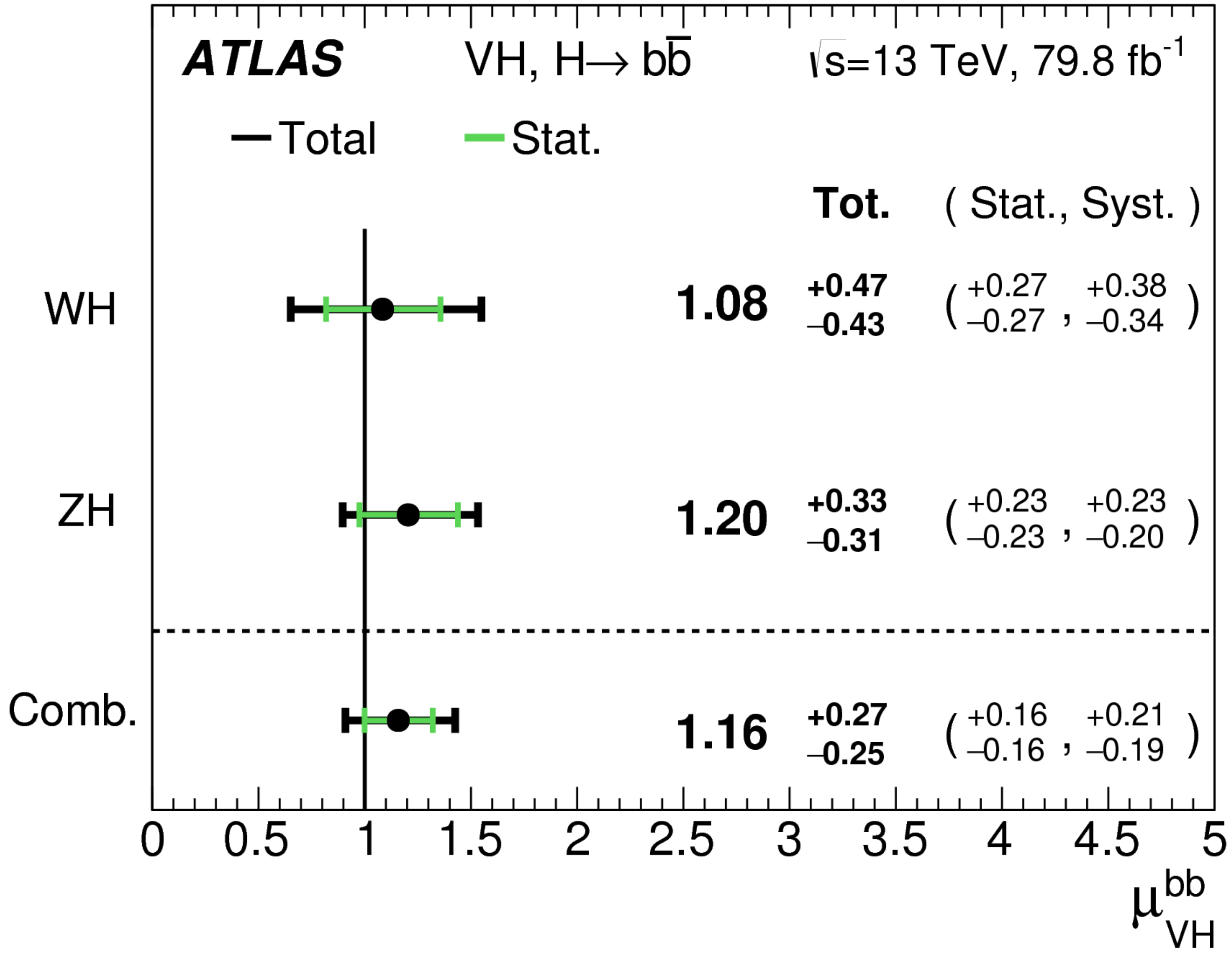
VH, H→bb analysis results (79.8fb^{-1})

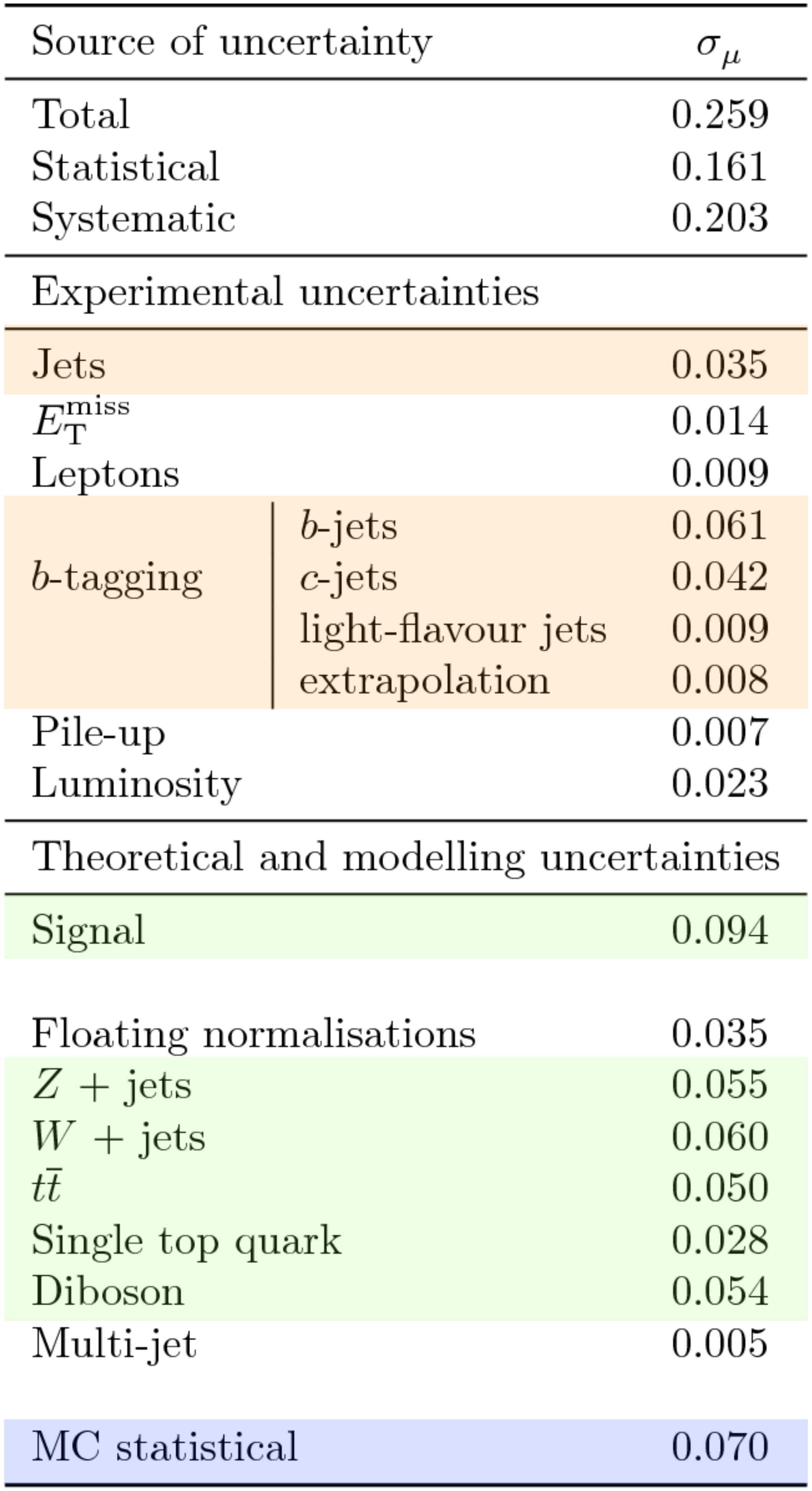
Observed (Expected) significance: 4.9 σ (4.3 σ).

The measured signal strength is

$$\mu_{VH}^{bb} = 1.16^{+0.27}_{-0.25} = 1.16 \pm 0.16(\text{stat.})^{+0.21}_{-0.19}(\text{syst.})$$

which is in good agreement with the SM prediction.





Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b-tagging	*b*-jets	0.061
	c-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

VH, H→bb analysis results (79.8fb^{-1})

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Total		0.259
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Systematic		0.203
Experimental uncertainties		
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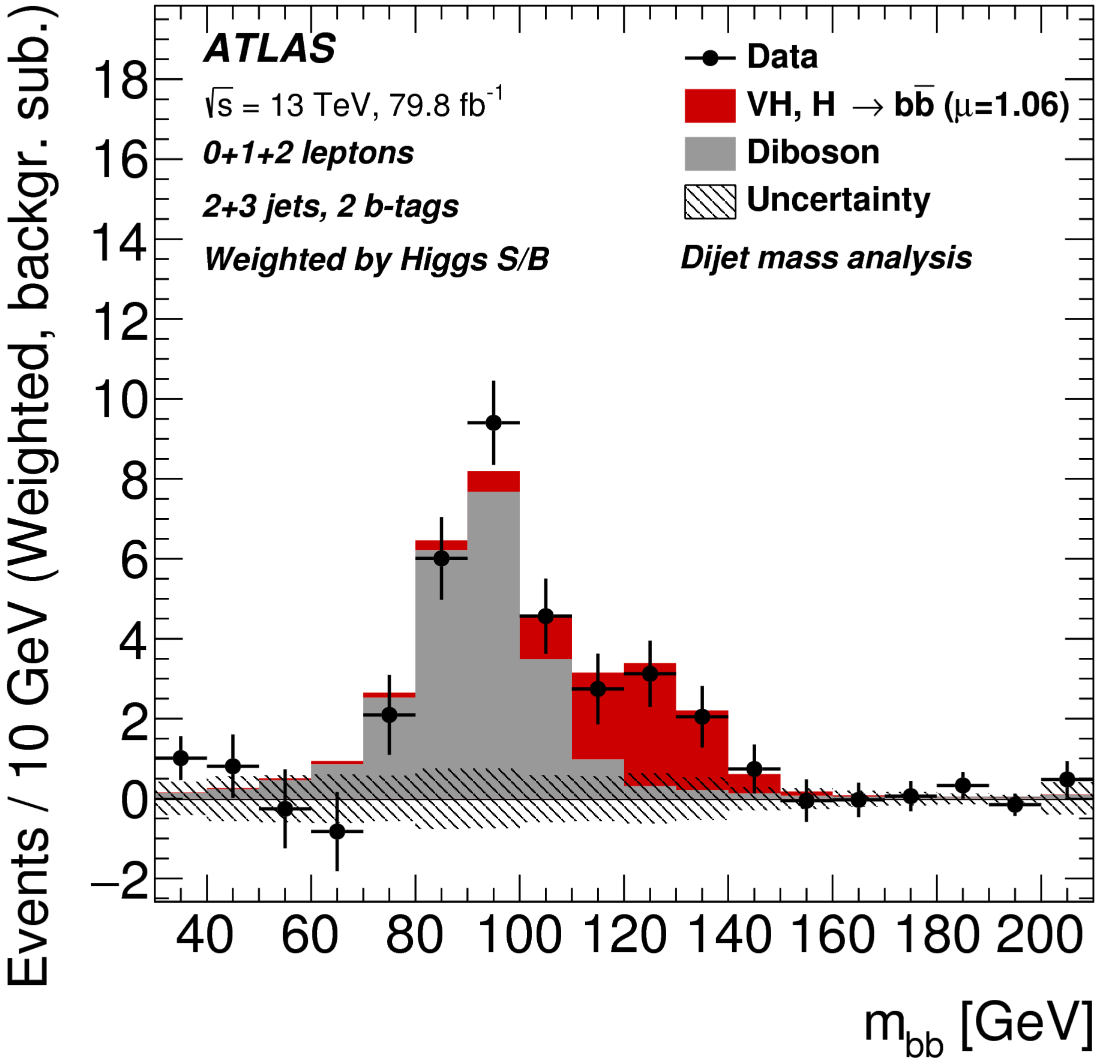
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

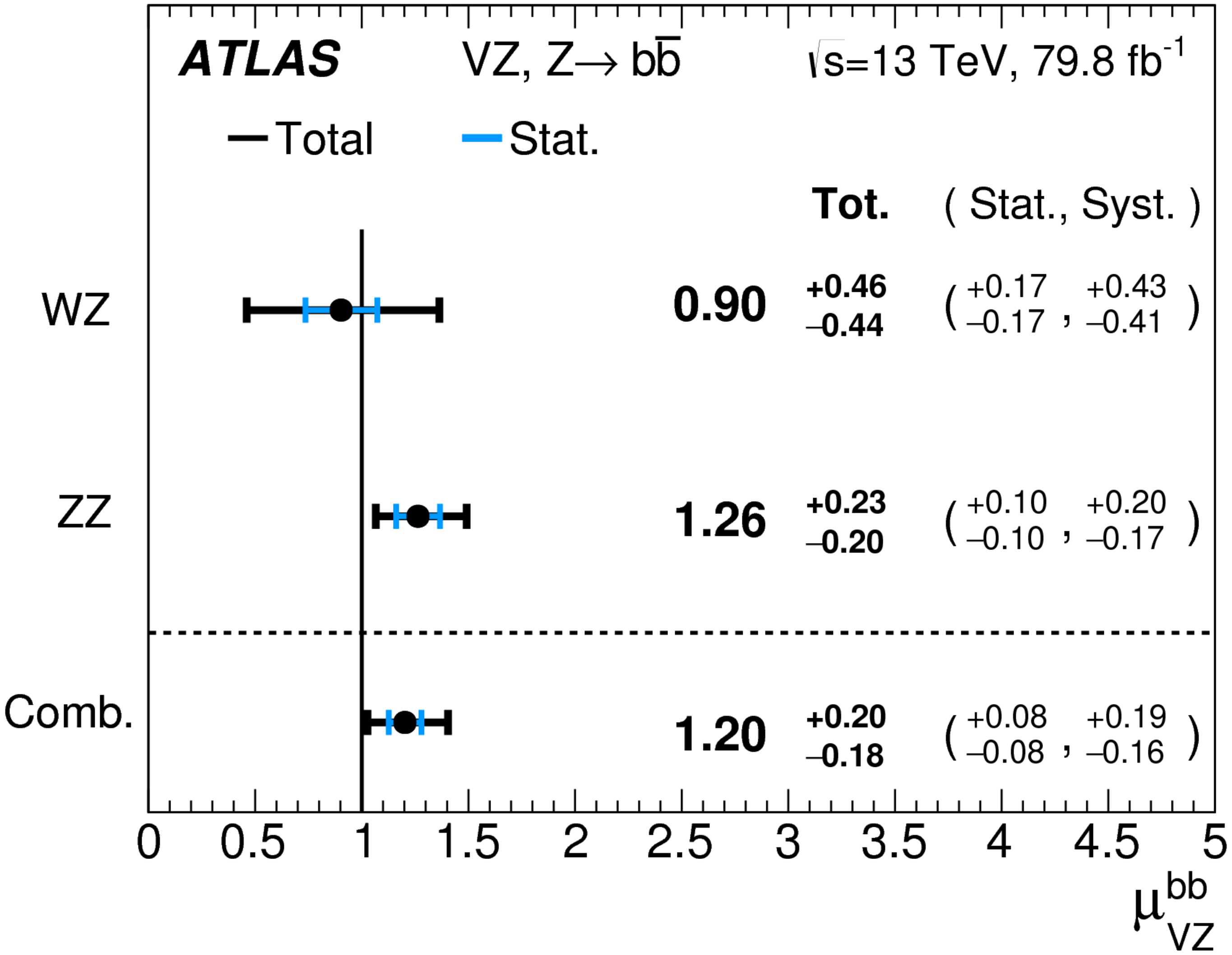
c-jets: from 0/1-lepton channels ttbar_bc contamination. ☜

W+jets: the leading uncertainty is Wpt from MadGraph vs Sherpa → need more consistent generators comparison and/or more direct data constrain. ☜

We are constantly trying to improve it with filters. ☜

Results from the two cross check analyses (79.8fb^{-1})





Dijet-mass analysis:

- ✦ Observed (Expected) significance: 3.6 σ (3.5 σ)
- ✦ The measured signal strength is:

$$\mu_{VH}^{bb} = 1.06^{+0.36}_{-0.33} = 1.06 \pm 0.20(\text{stat.})^{+0.30}_{-0.26}(\text{syst.})$$

Diboson analysis:

The measured VZ(Z→bb) signal strength is in good agreement with the SM prediction:

$$\mu_{VZ}^{bb} = 1.20^{+0.20}_{-0.18} = 1.20 \pm 0.08(\text{stat.})^{+0.19}_{-0.16}(\text{syst.})$$

Observation of H→bb decay mode

H→bb discovery is achieved in the combination of

- VH, ttH, VHF+ggF production channels
- Run 1 and Run 2 combination

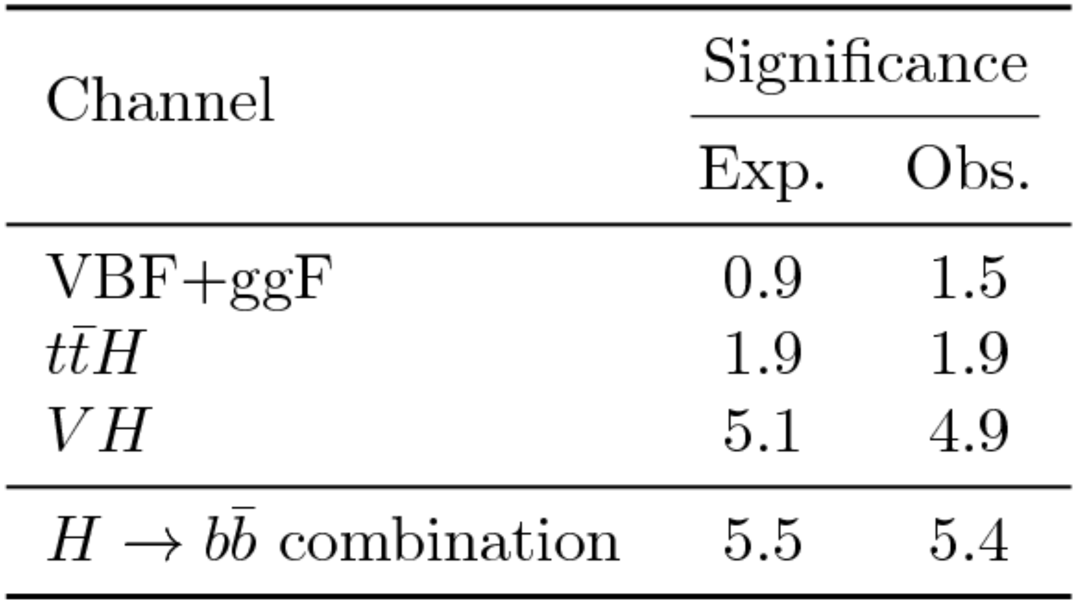
Observed (Expected) significance is 5.4σ (5.5σ).

The measured signal strength of H→bb is

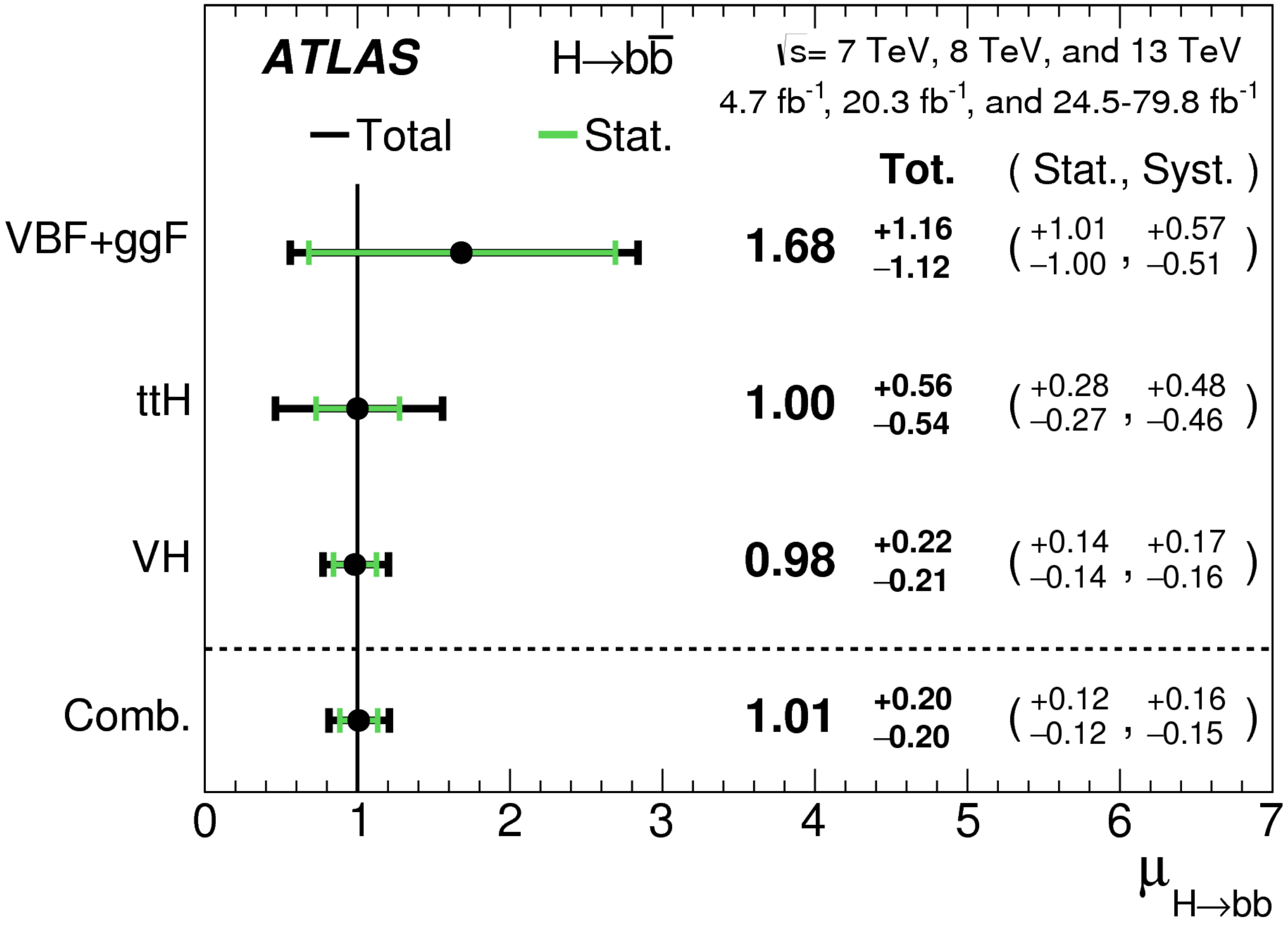
$$\mu_{H\to bb} = 1.01 \pm 0.20 = 1.01 \pm 0.12(\text{stat.})^{+0.16}_{-0.15}(\text{syst.})$$

which is in good agreement with the SM prediction.

The probability of compatibility of signal strength of the three production channels is 83%.



Channel	Significance Exp.	Significance Obs.
VBF+ggF	0.9	1.5
$t\bar{t}H$	1.9	1.9
VH	5.1	4.9
$H \to b\bar{b}$ combination	5.5	5.4



Observation of VH production channel

VH discovery is achieved in the combination of Higgs to ZZ/$\gamma\gamma$/bb decay modes.

Observed (Expected) significance is 5.3σ (4.8σ).

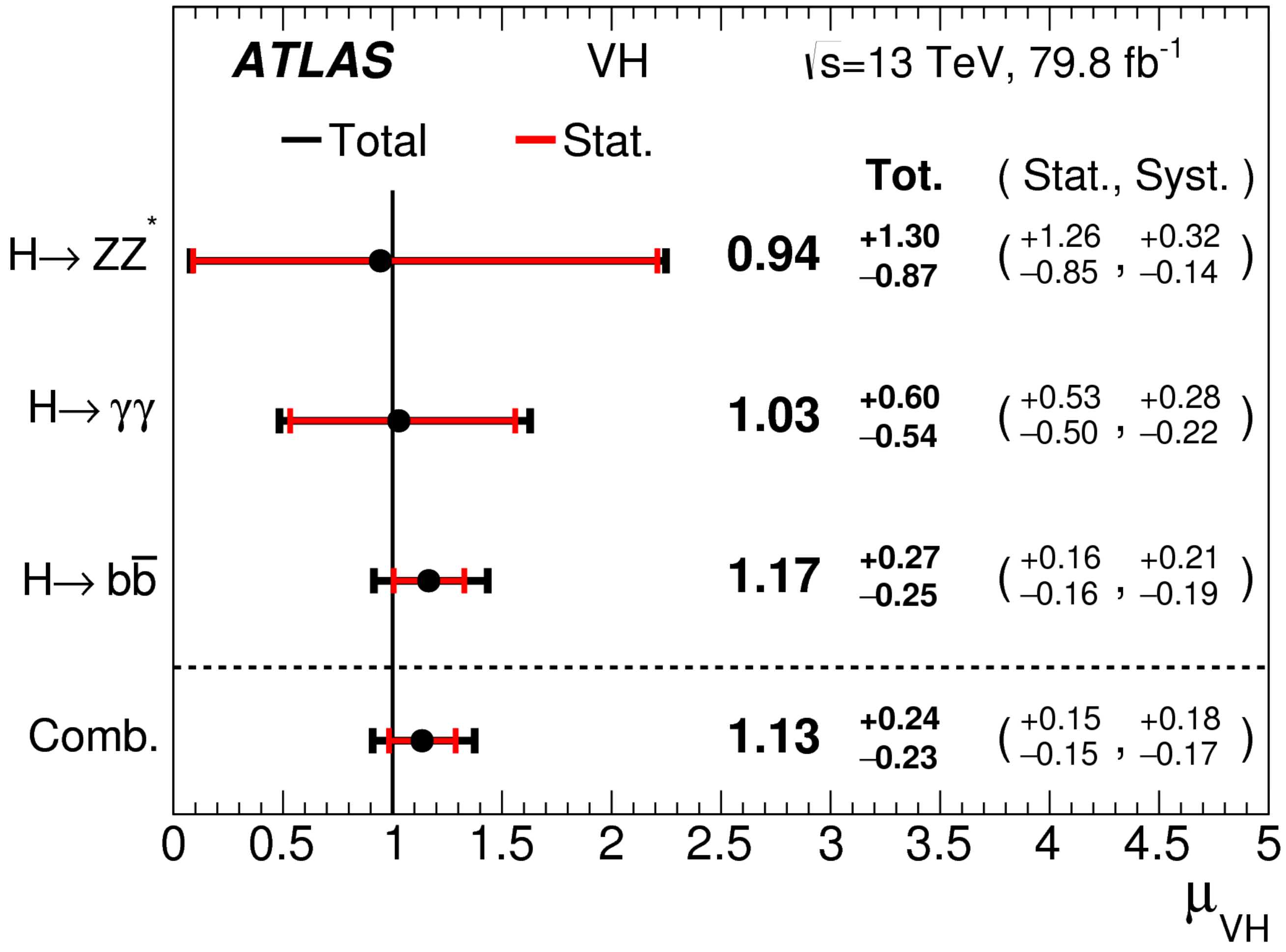
The measured signal strength of VH production is

$$\mu_{VH} = 1.13^{+0.24}_{-0.23} = 1.13 \pm 0.15(\text{stat.})^{+0.18}_{-0.17}(\text{syst.})$$

which is in good agreement with the SM prediction.

The probability of compatibility of signal strength of the three decay modes is 96%.

Channel	Significance	
	Exp.	Obs.
$H \to ZZ^* \to 4\ell$	1.1	1.1
$H \to \gamma\gamma$	1.9	1.9
$H \to b\bar{b}$	4.3	4.9
VH combined	4.8	5.3



Summary

VH, H→bb search has been performed in ATLAS experiment using 79.8 fb^{-1} Run 2 dataset

- observed (expected) significance is 4.9 σ (4.3 σ)
- the measured signal strength is

$$\mu_{VH}^{bb} = 1.16^{+0.27}_{-0.25} = 1.16 \pm 0.16(\text{stat.})^{+0.21}_{-0.19}(\text{syst.})$$

H→bb observation in the combination of VH, ttH, VBF and ggF production channels

- observed (expected) significance is 5.4 σ (5.5 σ)
- the measured signal strength is

$$\mu_{H\to bb} = 1.01 \pm 0.20 = 1.01 \pm 0.12(\text{stat.})^{+0.16}_{-0.15}(\text{syst.})$$

VH production observation in the combination of H→bb, H→ZZ→4l and H→$\gamma\gamma$ decay modes

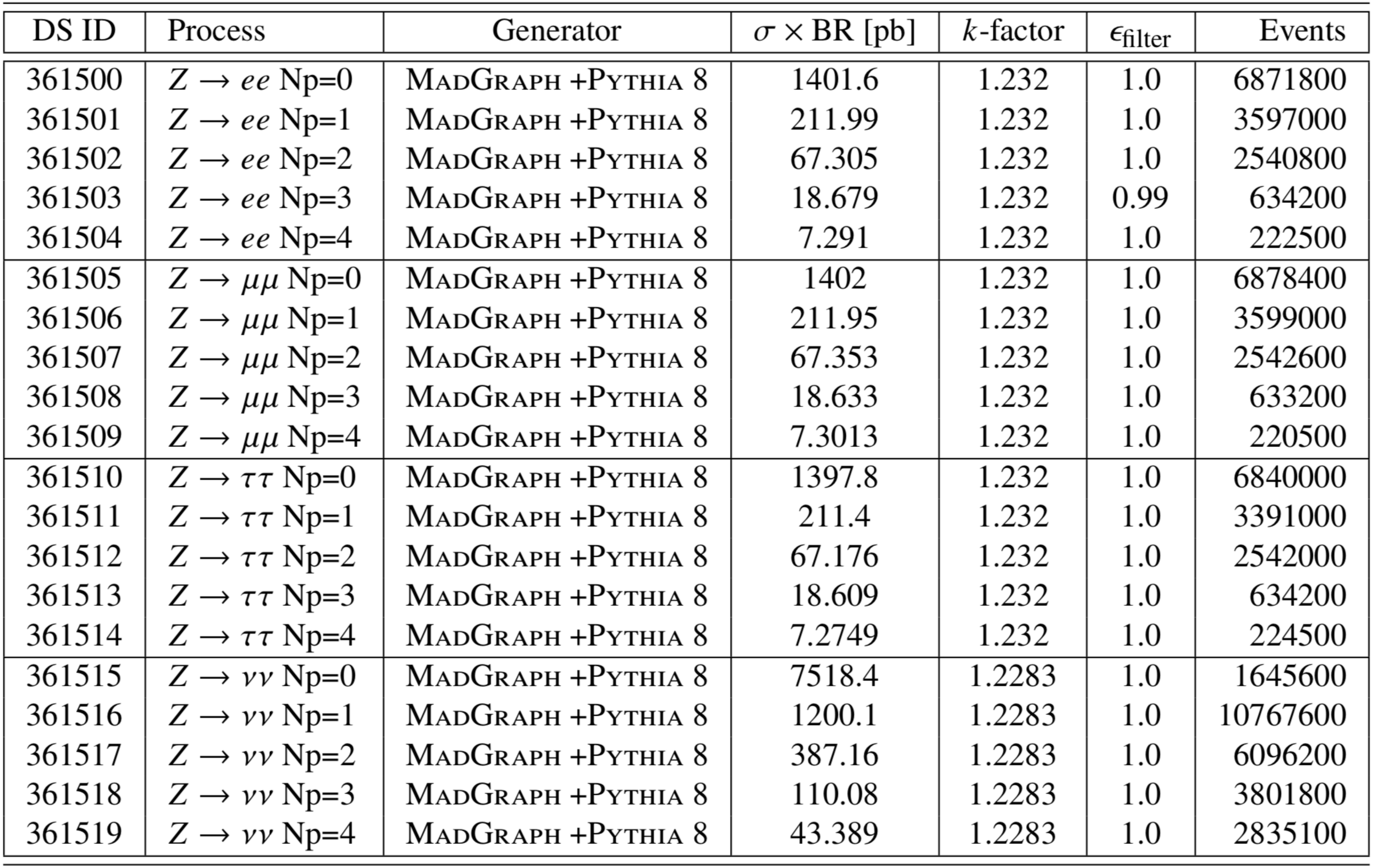
- observed (expected) significance is 5.3 σ (4.8 σ)
- the measured signal strength is

$$\mu_{VH} = 1.13^{+0.24}_{-0.23} = 1.13 \pm 0.15(\text{stat.})^{+0.18}_{-0.17}(\text{syst.})$$

The measures are in good agreement with the SM predictions.

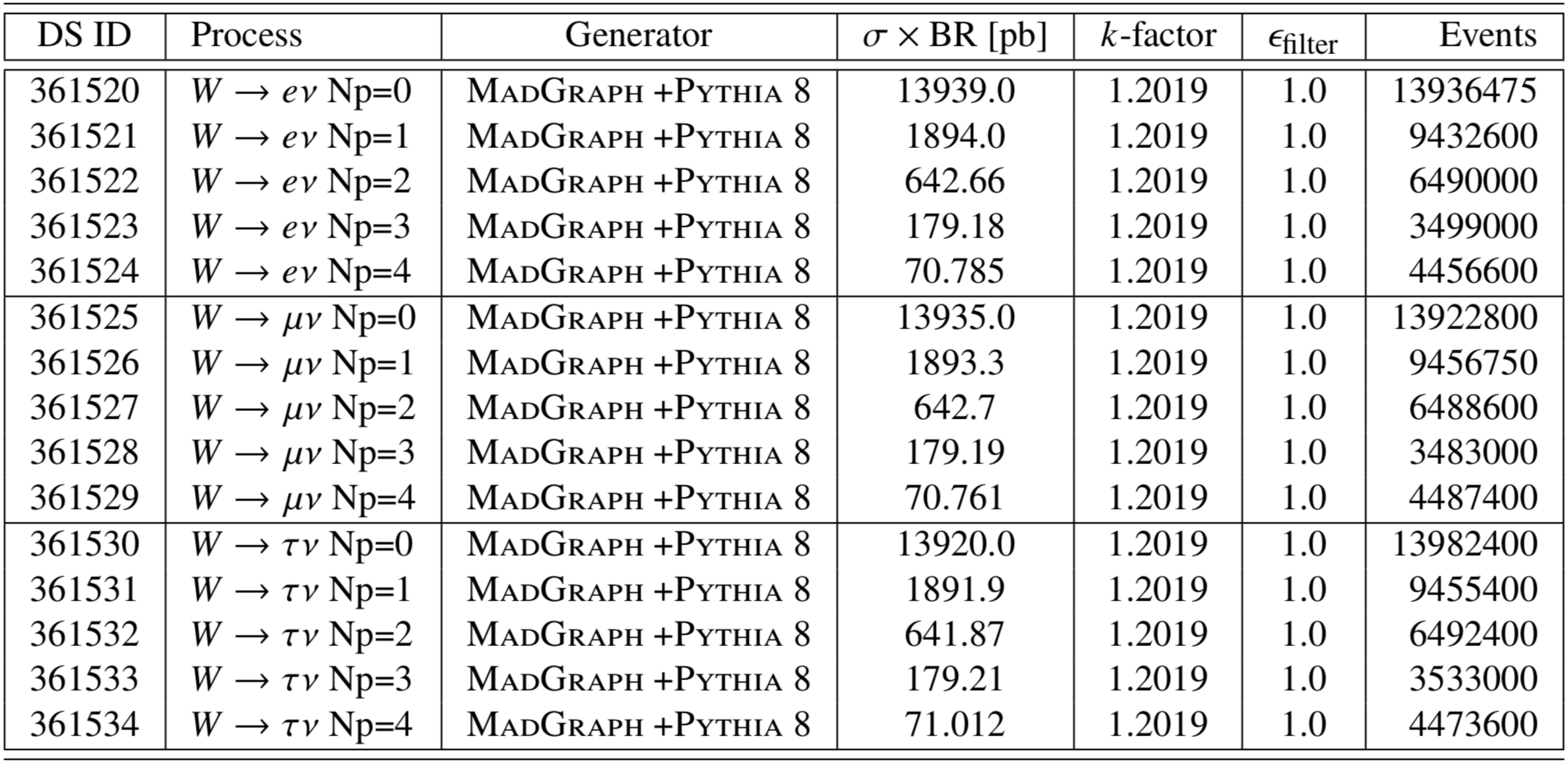
Backup

Alternative samples for modelling systematics - Z+jets



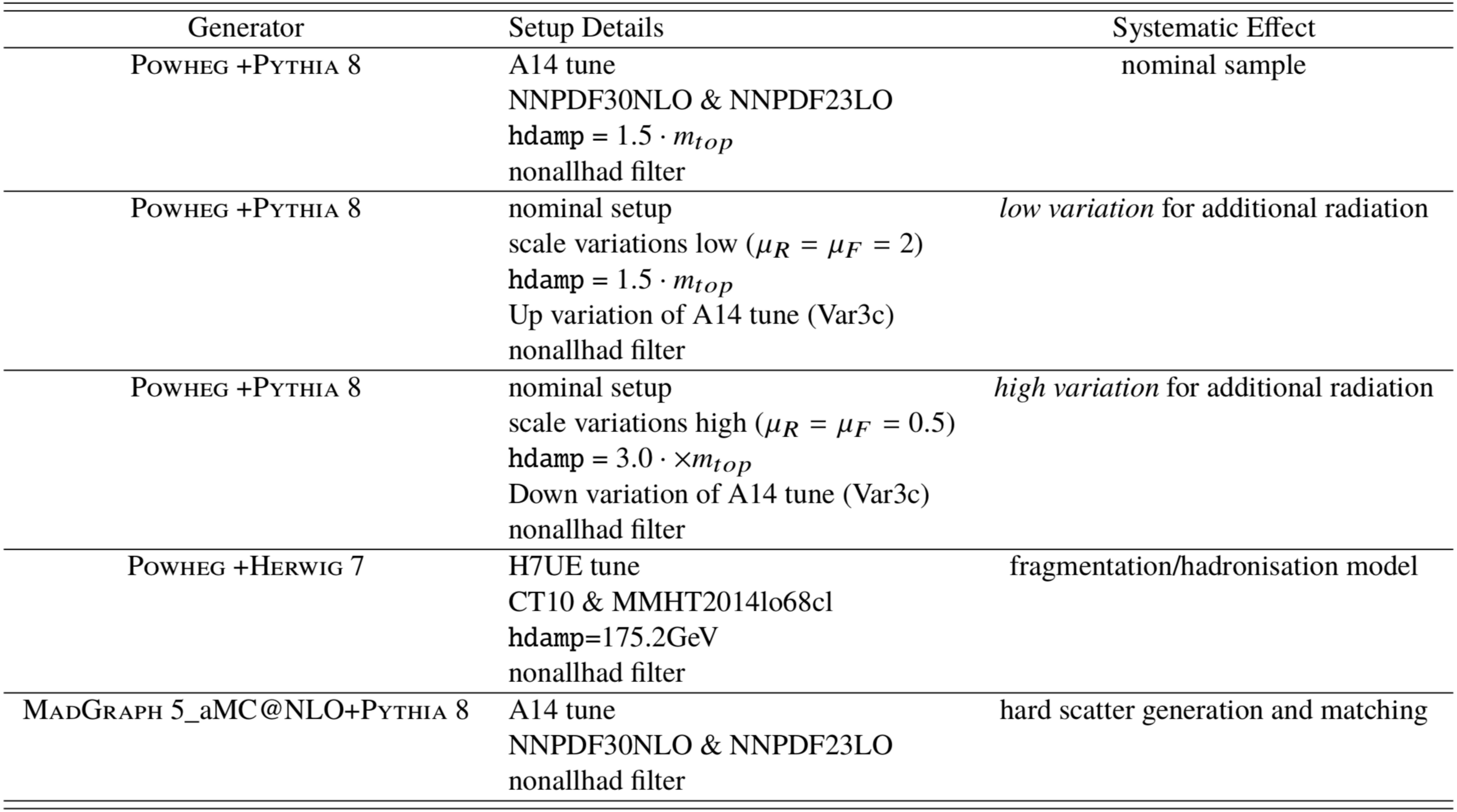
DS ID	Process	Generator	$\sigma \times$ BR [pb]	k-factor	ϵ_{filter}	Events
361500	$Z \rightarrow ee$ Np=0	MadGraph +Pythia 8	1401.6	1.232	1.0	6871800
361501	$Z \rightarrow ee$ Np=1	MadGraph +Pythia 8	211.99	1.232	1.0	3597000
361502	$Z \rightarrow ee$ Np=2	MadGraph +Pythia 8	67.305	1.232	1.0	2540800
361503	$Z \rightarrow ee$ Np=3	MadGraph +Pythia 8	18.679	1.232	0.99	634200
361504	$Z \rightarrow ee$ Np=4	MadGraph +Pythia 8	7.291	1.232	1.0	222500
361505	$Z \rightarrow \mu\mu$ Np=0	MadGraph +Pythia 8	1402	1.232	1.0	6878400
361506	$Z \rightarrow \mu\mu$ Np=1	MadGraph +Pythia 8	211.95	1.232	1.0	3599000
361507	$Z \rightarrow \mu\mu$ Np=2	MadGraph +Pythia 8	67.353	1.232	1.0	2542600
361508	$Z \rightarrow \mu\mu$ Np=3	MadGraph +Pythia 8	18.633	1.232	1.0	633200
361509	$Z \rightarrow \mu\mu$ Np=4	MadGraph +Pythia 8	7.3013	1.232	1.0	220500
361510	$Z \rightarrow \tau\tau$ Np=0	MadGraph +Pythia 8	1397.8	1.232	1.0	6840000
361511	$Z \rightarrow \tau\tau$ Np=1	MadGraph +Pythia 8	211.4	1.232	1.0	3391000
361512	$Z \rightarrow \tau\tau$ Np=2	MadGraph +Pythia 8	67.176	1.232	1.0	2542000
361513	$Z \rightarrow \tau\tau$ Np=3	MadGraph +Pythia 8	18.609	1.232	1.0	634200
361514	$Z \rightarrow \tau\tau$ Np=4	MadGraph +Pythia 8	7.2749	1.232	1.0	224500
361515	$Z \rightarrow \nu\nu$ Np=0	MadGraph +Pythia 8	7518.4	1.2283	1.0	1645600
361516	$Z \rightarrow \nu\nu$ Np=1	MadGraph +Pythia 8	1200.1	1.2283	1.0	10767600
361517	$Z \rightarrow \nu\nu$ Np=2	MadGraph +Pythia 8	387.16	1.2283	1.0	6096200
361518	$Z \rightarrow \nu\nu$ Np=3	MadGraph +Pythia 8	110.08	1.2283	1.0	3801800
361519	$Z \rightarrow \nu\nu$ Np=4	MadGraph +Pythia 8	43.389	1.2283	1.0	2835100

Alternative samples for modelling systematics - W+jets



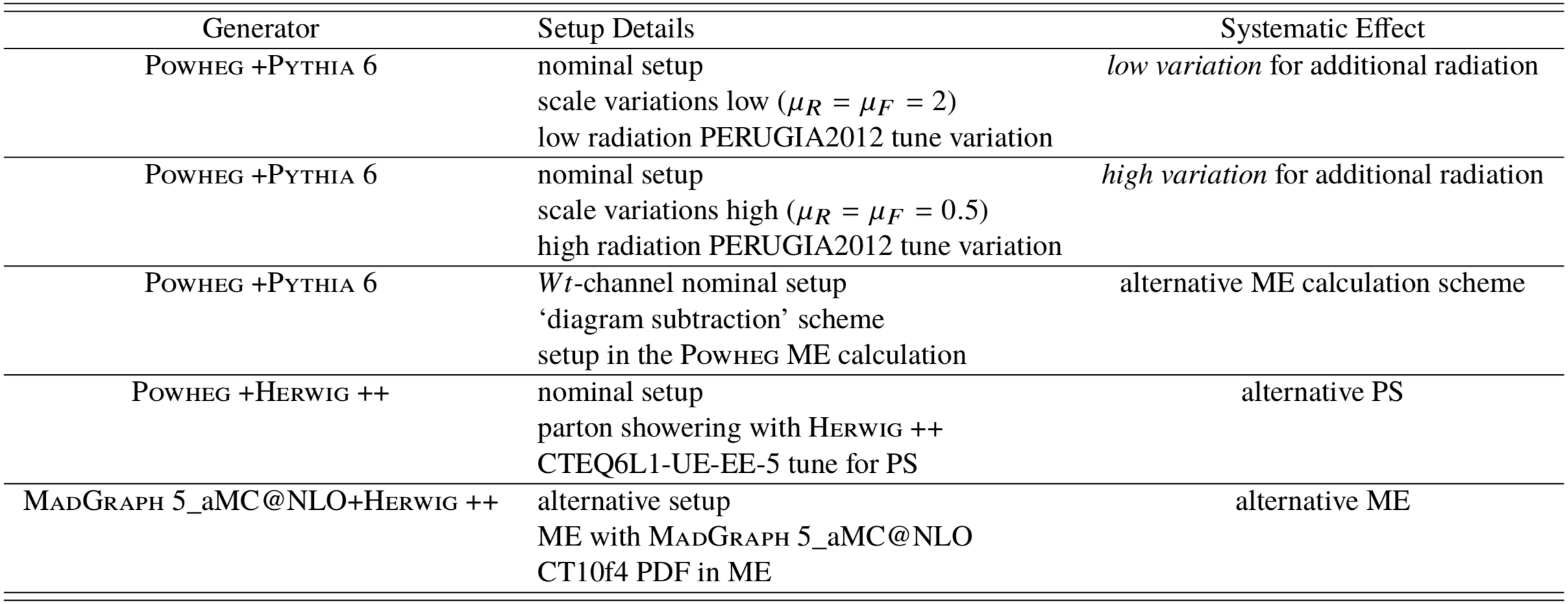
DS ID	Process	Generator	$\sigma \times$ BR [pb]	k-factor	ϵ_{filter}	Events
361520	$W \rightarrow e\nu$ Np=0	MadGraph +Pythia 8	13939.0	1.2019	1.0	13936475
361521	$W \rightarrow e\nu$ Np=1	MadGraph +Pythia 8	1894.0	1.2019	1.0	9432600
361522	$W \rightarrow e\nu$ Np=2	MadGraph +Pythia 8	642.66	1.2019	1.0	6490000
361523	$W \rightarrow e\nu$ Np=3	MadGraph +Pythia 8	179.18	1.2019	1.0	3499000
361524	$W \rightarrow e\nu$ Np=4	MadGraph +Pythia 8	70.785	1.2019	1.0	4456600
361525	$W \rightarrow \mu\nu$ Np=0	MadGraph +Pythia 8	13935.0	1.2019	1.0	13922800
361526	$W \rightarrow \mu\nu$ Np=1	MadGraph +Pythia 8	1893.3	1.2019	1.0	9456750
361527	$W \rightarrow \mu\nu$ Np=2	MadGraph +Pythia 8	642.7	1.2019	1.0	6488600
361528	$W \rightarrow \mu\nu$ Np=3	MadGraph +Pythia 8	179.19	1.2019	1.0	3483000
361529	$W \rightarrow \mu\nu$ Np=4	MadGraph +Pythia 8	70.761	1.2019	1.0	4487400
361530	$W \rightarrow \tau\nu$ Np=0	MadGraph +Pythia 8	13920.0	1.2019	1.0	13982400
361531	$W \rightarrow \tau\nu$ Np=1	MadGraph +Pythia 8	1891.9	1.2019	1.0	9455400
361532	$W \rightarrow \tau\nu$ Np=2	MadGraph +Pythia 8	641.87	1.2019	1.0	6492400
361533	$W \rightarrow \tau\nu$ Np=3	MadGraph +Pythia 8	179.21	1.2019	1.0	3533000
361534	$W \rightarrow \tau\nu$ Np=4	MadGraph +Pythia 8	71.012	1.2019	1.0	4473600

Alternative samples for modelling systematics - ttbar



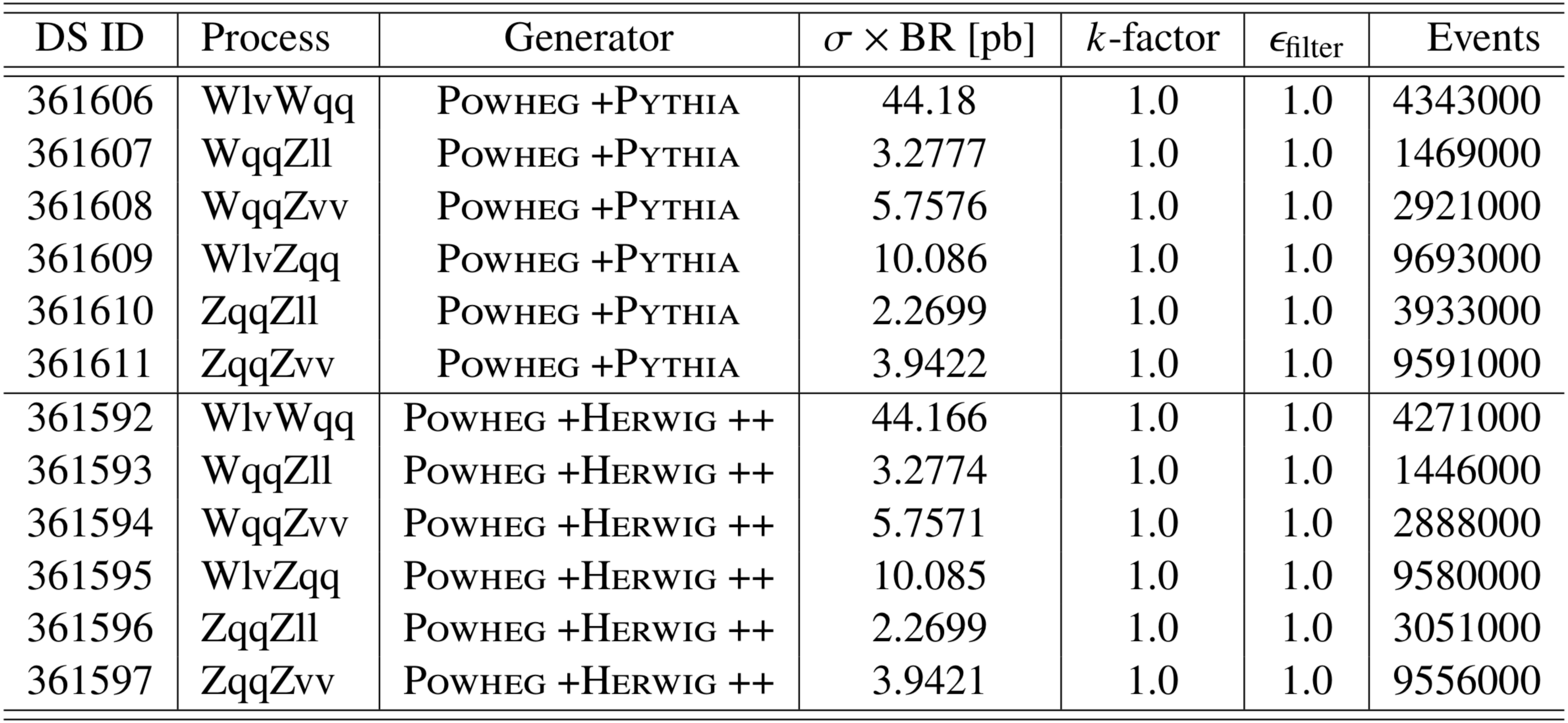
Generator	Setup Details	Systematic Effect
Powheg +Pythia 8	A14 tune NNPDF30NLO & NNPDF23LO `hdamp` = $1.5 \cdot m_{top}$ nonallhad filter	nominal sample
Powheg +Pythia 8	nominal setup scale variations low ($\mu_R = \mu_F = 2$) `hdamp` = $1.5 \cdot m_{top}$ Up variation of A14 tune (Var3c) nonallhad filter	*low variation* for additional radiation
Powheg +Pythia 8	nominal setup scale variations high ($\mu_R = \mu_F = 0.5$) `hdamp` = $3.0 \cdot \times m_{top}$ Down variation of A14 tune (Var3c) nonallhad filter	*high variation* for additional radiation
Powheg +Herwig 7	H7UE tune CT10 & MMHT2014lo68cl `hdamp`=175.2GeV nonallhad filter	fragmentation/hadronisation model
MadGraph 5_aMC@NLO+Pythia 8	A14 tune NNPDF30NLO & NNPDF23LO nonallhad filter	hard scatter generation and matching

Alternative samples for modelling systematics - single-top



Generator	Setup Details	Systematic Effect
Powheg +Pythia 6	nominal setup scale variations low ($\mu_R = \mu_F = 2$) low radiation PERUGIA2012 tune variation	*low variation* for additional radiation
Powheg +Pythia 6	nominal setup scale variations high ($\mu_R = \mu_F = 0.5$) high radiation PERUGIA2012 tune variation	*high variation* for additional radiation
Powheg +Pythia 6	Wt-channel nominal setup ‘diagram subtraction’ scheme setup in the Powheg ME calculation	alternative ME calculation scheme
Powheg +Herwig ++	nominal setup parton showering with Herwig ++ CTEQ6L1-UE-EE-5 tune for PS	alternative PS
MadGraph 5_aMC@NLO+Herwig ++	alternative setup ME with MadGraph 5_aMC@NLO CT10f4 PDF in ME	alternative ME

Alternative samples for modelling systematics - di-boson



DS ID	Process	Generator	$\sigma \times$ BR [pb]	k-factor	ϵ_{filter}	Events
361606	WlvWqq	Powheg +Pythia	44.18	1.0	1.0	4343000
361607	WqqZll	Powheg +Pythia	3.2777	1.0	1.0	1469000
361608	WqqZvv	Powheg +Pythia	5.7576	1.0	1.0	2921000
361609	WlvZqq	Powheg +Pythia	10.086	1.0	1.0	9693000
361610	ZqqZll	Powheg +Pythia	2.2699	1.0	1.0	3933000
361611	ZqqZvv	Powheg +Pythia	3.9422	1.0	1.0	9591000
361592	WlvWqq	Powheg +Herwig ++	44.166	1.0	1.0	4271000
361593	WqqZll	Powheg +Herwig ++	3.2774	1.0	1.0	1446000
361594	WqqZvv	Powheg +Herwig ++	5.7571	1.0	1.0	2888000
361595	WlvZqq	Powheg +Herwig ++	10.085	1.0	1.0	9580000
361596	ZqqZll	Powheg +Herwig ++	2.2699	1.0	1.0	3051000
361597	ZqqZvv	Powheg +Herwig ++	3.9421	1.0	1.0	9556000

Multi-jets background estimate and uncertainty

Multi-jet backgrounds are negligible in the 2-lep channel as well as the 0-lep channel after anti-QCD cut.

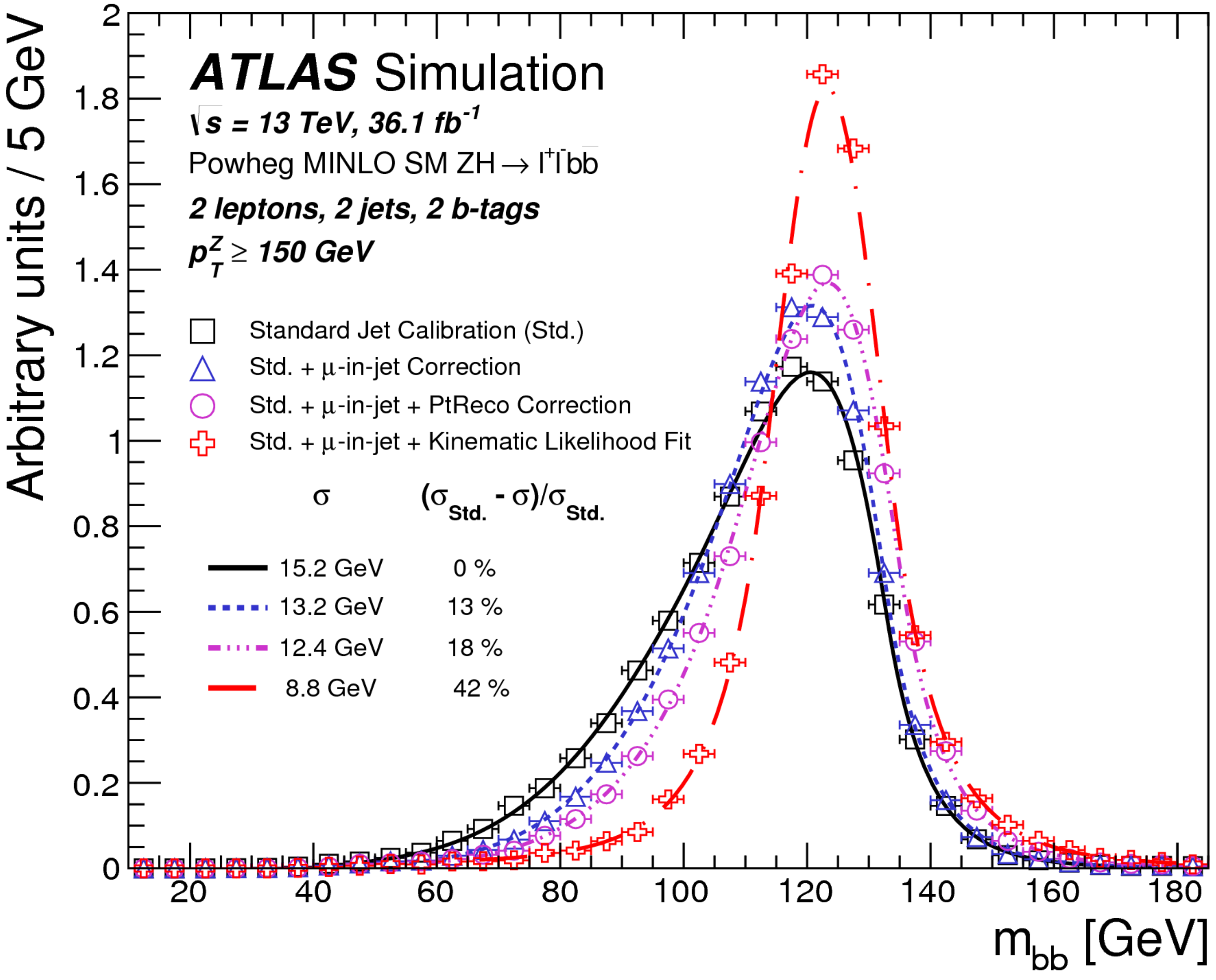
Multi-jet background in the 1-lepton channel

- constitutes 2-3% of the total in 2-jet and <0.5% in 3-jet categories
- Estimation:
  - **multi-jet enriched control region**: nominal selection, but exactly 1 b-tagged jet and inverting lepton isolation cut, in separated in electron/muon and 2-jet/3-jet categories.
  - **BDT shape** distribution is extracted from this control region
  - **overall normalisation**: fit in 1-lepton SR using mTW as template
    - multi-jet template is derived in this control region
    - other SM processes from MC estimates
- **systematic uncertainties**
  - verifying control region selection on isolation and trigger
  - verifying SM processes normalisation during the subtraction
  - only effect on normalisation
    - using delta-phi(lepton, bb) instead of mTW in the template fit
    - for electron channel only, inclusive of E_T-miss < 30 GeV events in the template fit.

Signal mass resolution and corrections

For b-tagged jets, in addition to the standard jet energy calibration, corrections to improve energy scale and resolution:

- ✓ four-momentum of the closer muon (∆R<0.4) is added to that of the jet
- ✓ a residual correction on jet pt is applied to equalise the response to jets with leptonic or hadronic decays of heavy-flavour hadrons
- ✓ for 2-lepton channel only, full reconstruction of the event kinematics using likelihood fit to improve b-jet energy estimates.



The corrections improve the resolution of the di-jet mass by up to 40% !

Breakdown of the contributions to the uncertainty in μ

Evidence paper (36.1 fb^{-1})

Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.03
Leptons		0.01
b-tagging	b-jets	0.09
	c-jets	0.04
	light jets	0.04
	extrapolation	0.01
Pile-up		0.01
Luminosity		0.04
Theoretical and modelling uncertainties		
Signal		0.17
Floating normalisations		0.07
Z + jets		0.07
W + jets		0.07
$t\bar{t}$		0.07
Single top quark		0.08
Diboson		0.02
Multijet		0.02
MC statistical		0.13

Observation paper (79.8 fb^{-1})

Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.014
Leptons		0.009
b-tagging	b-jets	0.061
	c-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

Ingredient 1: tune variations AZNLO

AZNLO: *designed for the Powheg+Pythia8 NLO+PS generator, and provide a very good description of ISR in the low and medium p_T region*

Measurements of the Z/γ_* boson transverse momentum distribution (and ϕ^*_η angular correlation) in pp collisions at $\sqrt{s}$ = 7 TeV

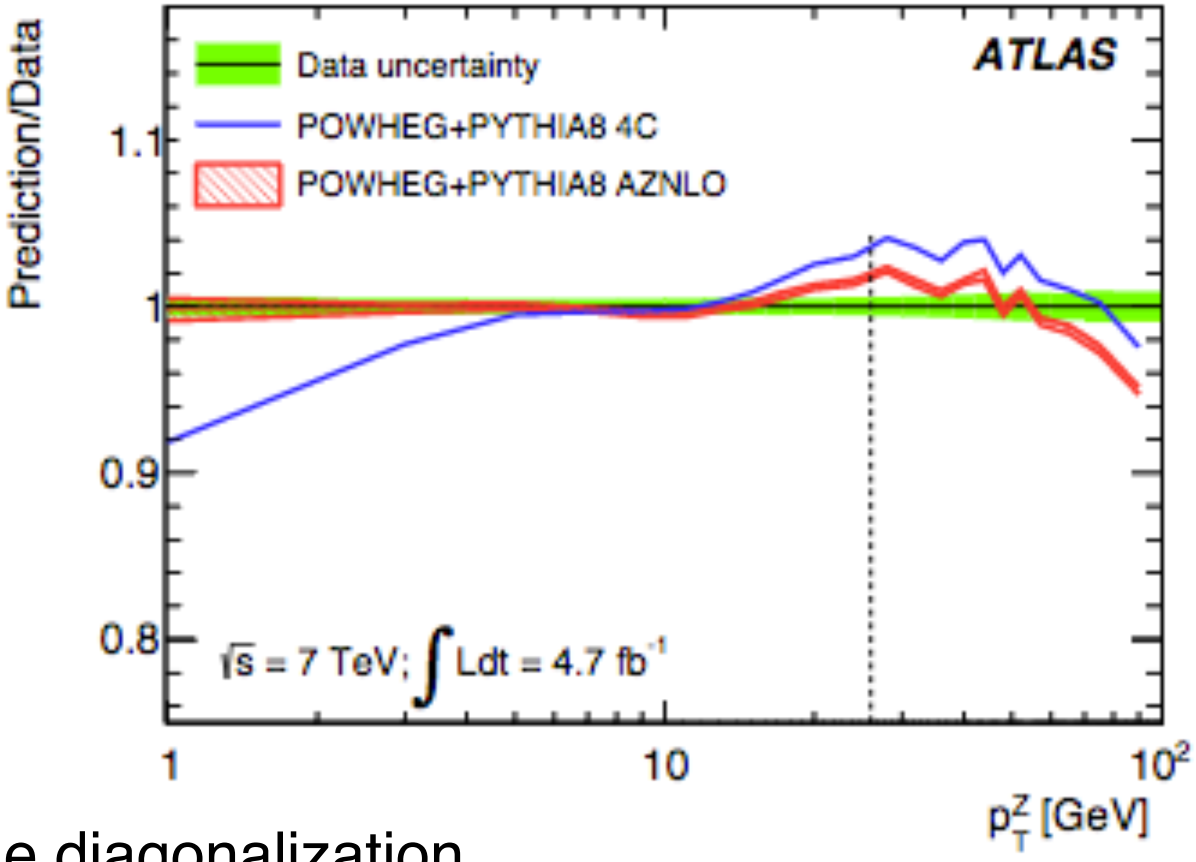
JHEP, 09:145, 2014

1211.6899

Strategy for the Powheg+Pythia8 tune → tunes performed for **$p_T(Z)$<26GeV** and ϕ^*_η<0.29 (best description of the tuning parameters)

The tuning only varies the ISR shower cut-off and the primordial k_T in Pythia8: essentially constrained by data $p_T(Z)$<12GeV - not affected by tuning upper bound (plus MPI parameters)

Tuned predictions agree with the measured XS within 2% for $p_T(Z)$<50GeV



“Eigentune variations”:

only covering ISR/primordial-k_T variations;
ren. scale variations for FSR, and MPI cut-off paramaters are recommended to cover the full range of UE/PS/MPI uncertainties

- VAR1,VAR2: eigentune diagonalization
- MPIUp, MPIDown
- FSRUp, FSRDown

Ingredient 1: tune variations AZNLO

AZNLO: ator, and
provide a v n p_T region

EP, 09:145, 2014

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Strategy for th

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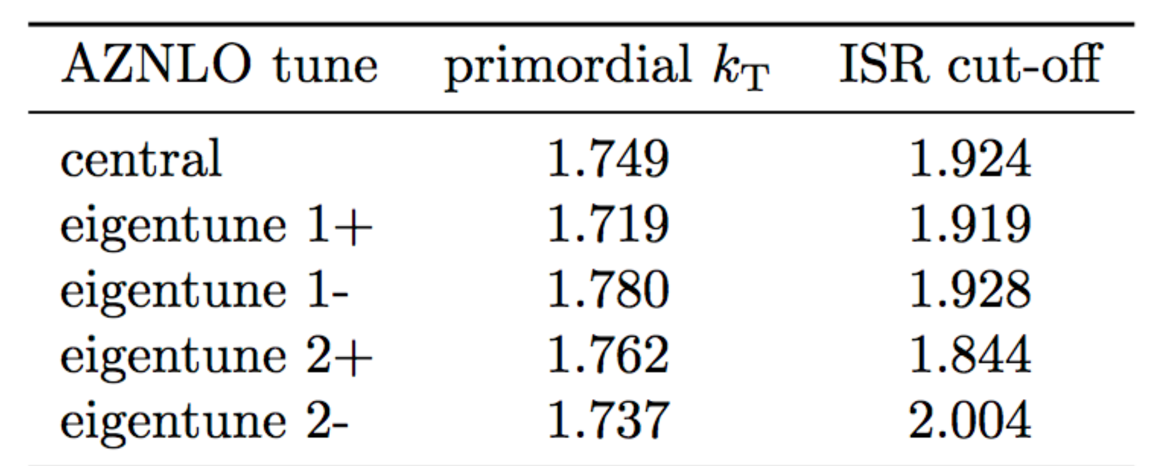
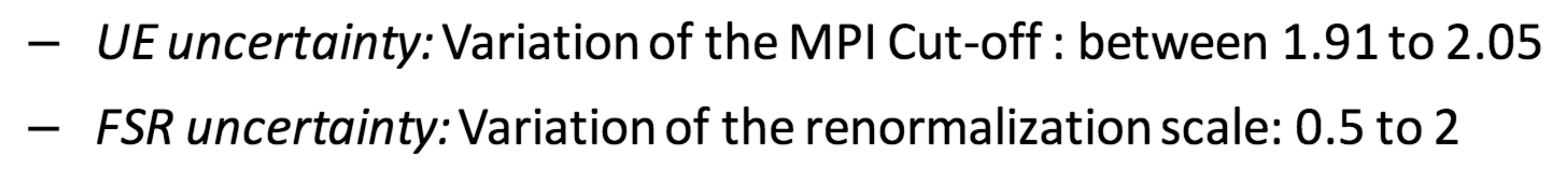
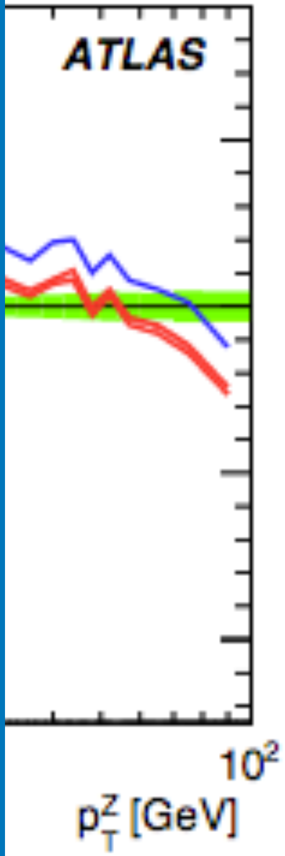


AZNLO tune	primordial k_T	ISR cut-off
central	1.749	1.924
eigentune 1+	1.719	1.919
eigentune 1-	1.780	1.928
eigentune 2+	1.762	1.844
eigentune 2-	1.737	2.004



- *UE uncertainty:* Variation of the MPI Cut-off : between 1.91 to 2.05
- *FSR uncertainty:* Variation of the renormalization scale: 0.5 to 2



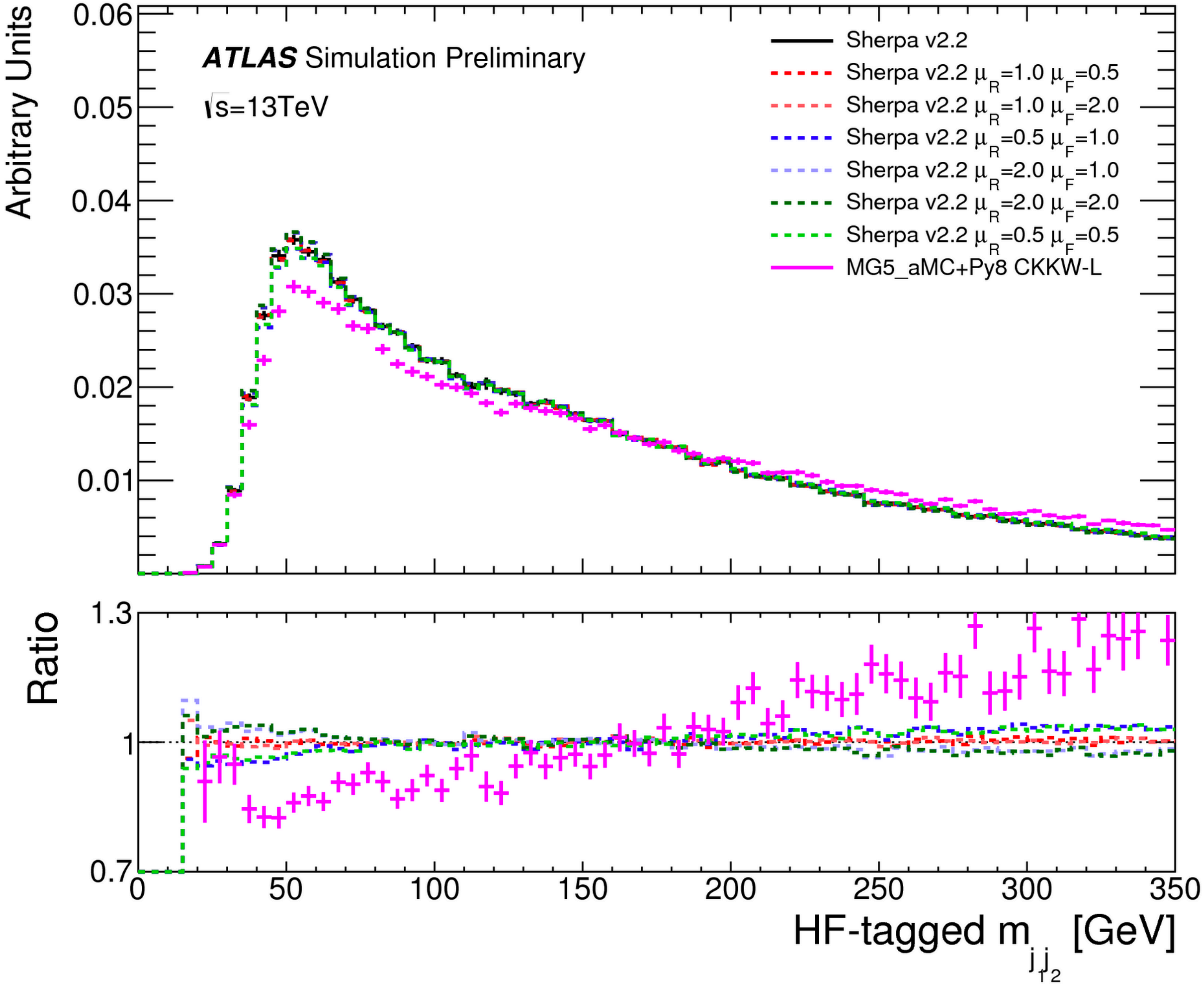
“Eigentune va

only covering ISR/p
ren. scale variations
paramaters are reco
UE/PS/MPI uncerta

V+jets background modeling

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2017-006/

ATLAS PUB not on V+jets modeling and MC simulation



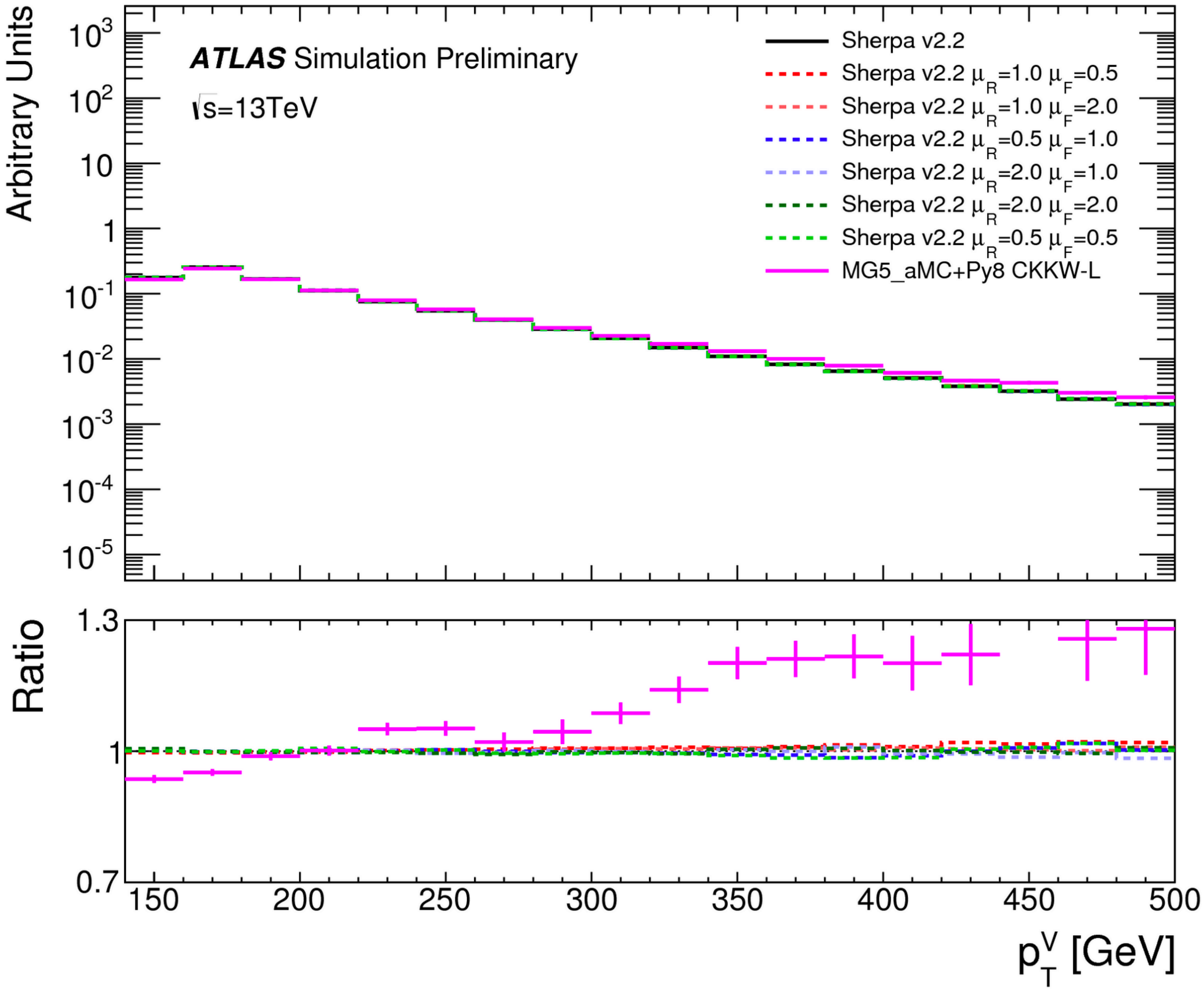
- **selection close to nominal VH(bb) analysis regions**

- no cut on #jets<=3
- no W+hf CR/SR separation

V+jets background modeling

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2017-006/

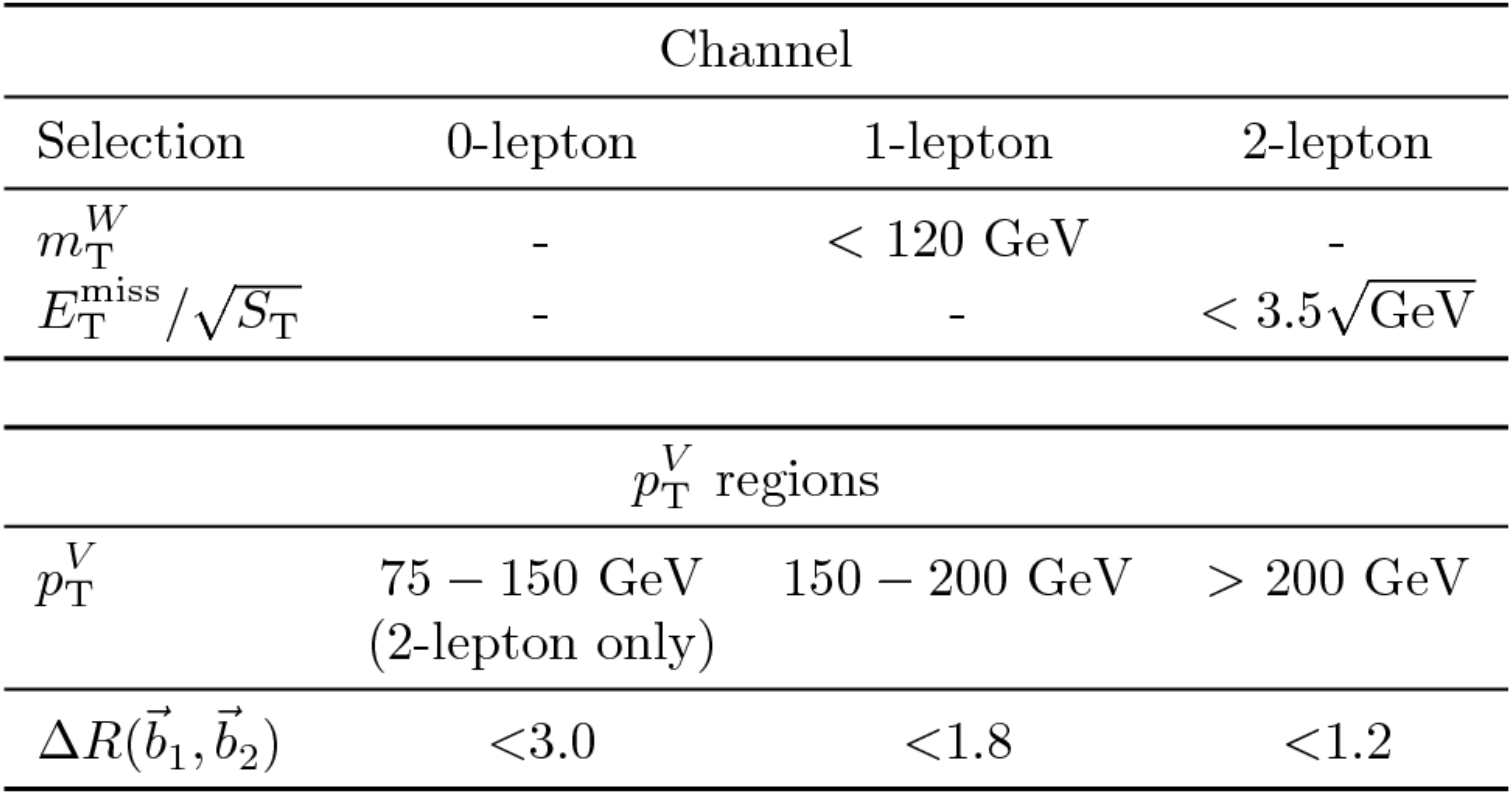
ATLAS PUB not on V+jets modeling and MC simulation



- **selection close to nominal VH(bb) analysis regions**

- no cut on #jets<=3
- no W+hf CR/SR separation

Event selection for the dijet-mass analysis addition to MVA analysis



	Channel		
Selection	0-lepton	1-lepton	2-lepton
m_{T}^{W}	-	< 120 GeV	-
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{S_{\mathrm{T}}}$	-	-	$< 3.5\sqrt{\mathrm{GeV}}$

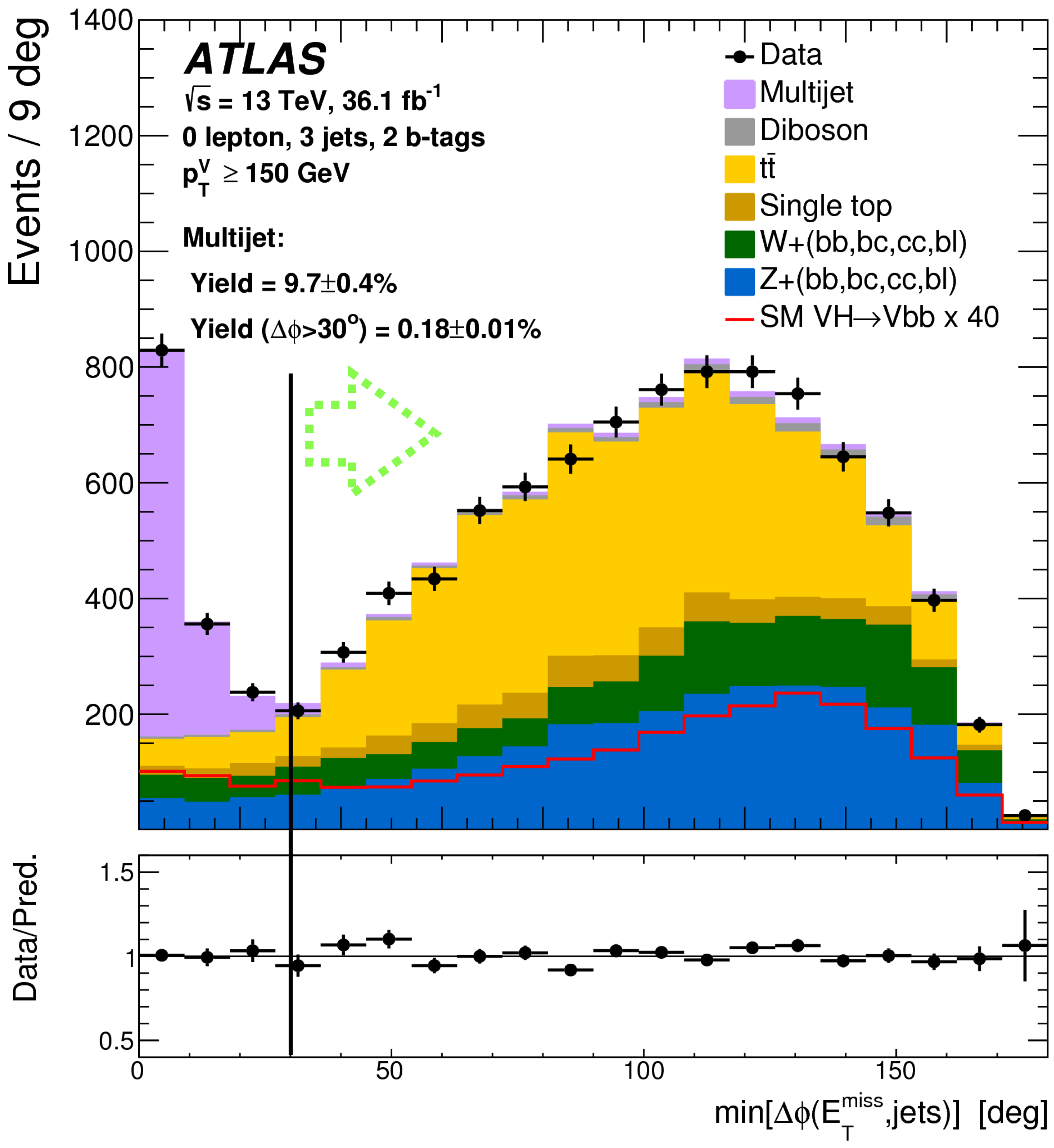
	p_{T}^{V} regions		
p_{T}^{V}	$75 - 150$ GeV (2-lepton only)	$150 - 200$ GeV	> 200 GeV
$\Delta R(\vec{b}_1, \vec{b}_2)$	<3.0	<1.8	<1.2

Variables used for the multivariate discriminants

Variable	0-lepton	1-lepton	2-lepton
p_{T}^{V}	$\equiv E_{\mathrm{T}}^{\mathrm{miss}}$	×	×
$E_{\mathrm{T}}^{\mathrm{miss}}$	×	×	
$p_{\mathrm{T}}^{b_1}$	×	×	×
$p_{\mathrm{T}}^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(\vec{b_1}, \vec{b_2})$	×	×	×
$\lvert\Delta\eta(\vec{b_1}, \vec{b_2})\rvert$	×		
$\Delta\phi(\vec{V}, \vec{bb})$	×	×	×
$\lvert\Delta\eta(\vec{V}, \vec{bb})\rvert$			×
m_{eff}	×		
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		×	
m_{T}^{W}		×	
$m_{\ell\ell}$			×
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{S_{\mathrm{T}}}$			×
m_{top}		×	
$\lvert\Delta Y(\vec{V}, \vec{bb})\rvert$		×	

	Only in 3-jet events		
$p_{\mathrm{T}}^{\mathrm{jet}_3}$	×	×	×
m_{bbj}	×	×	×

Multi-jet estimate in 0-lepton channel



$$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},\vec{\mathrm{jets}})] \quad > 20^\circ \ (2 \text{ jets}),\ > 30^\circ \ (3 \text{ jets})$$

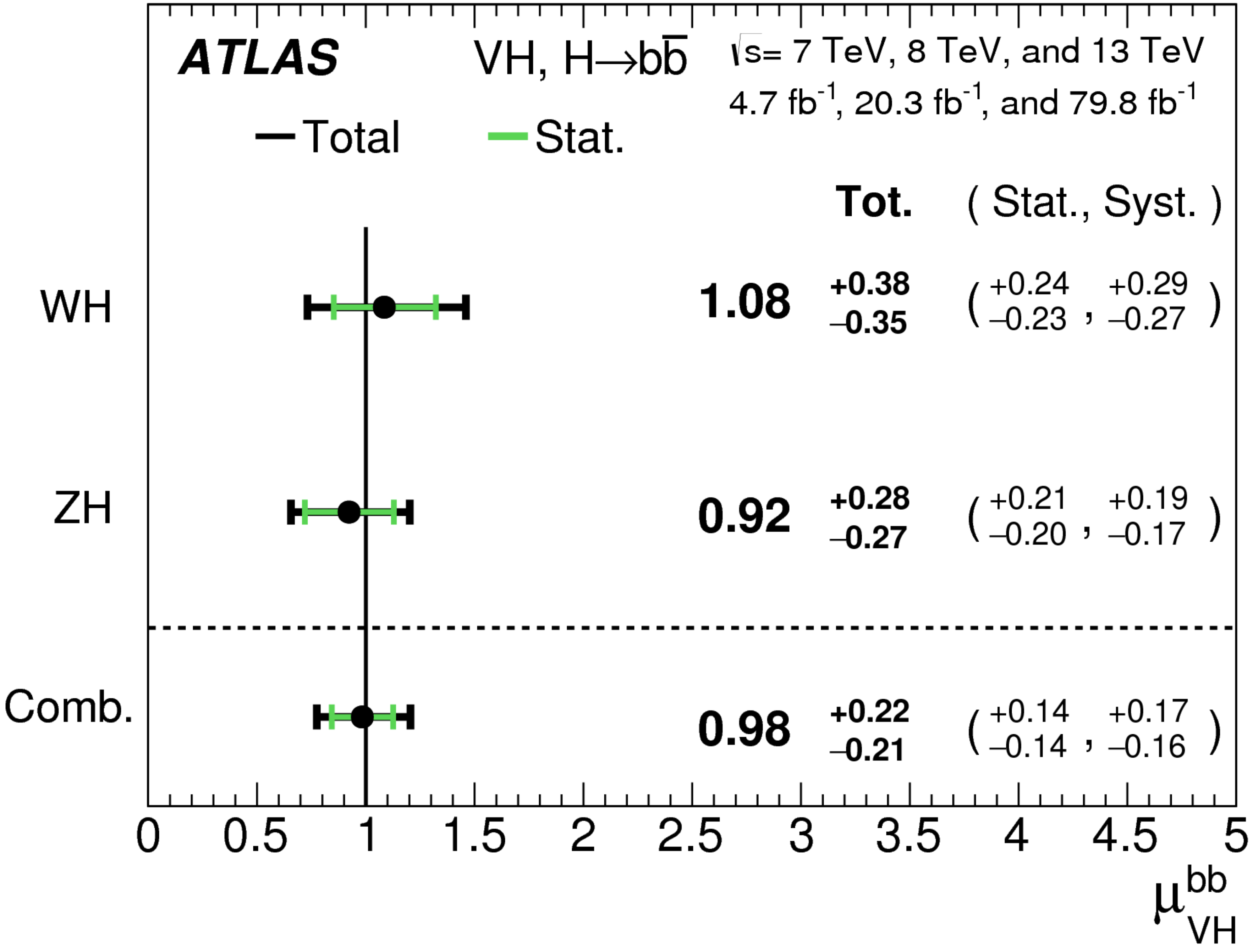
$$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},\vec{bb}) \quad > 120^\circ$$

$$\Delta\phi(\vec{b_1},\vec{b_2}) \quad < 140^\circ$$

$$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},\vec{p}_{\mathrm{T}}^{\mathrm{miss}}) \quad < 90^\circ$$

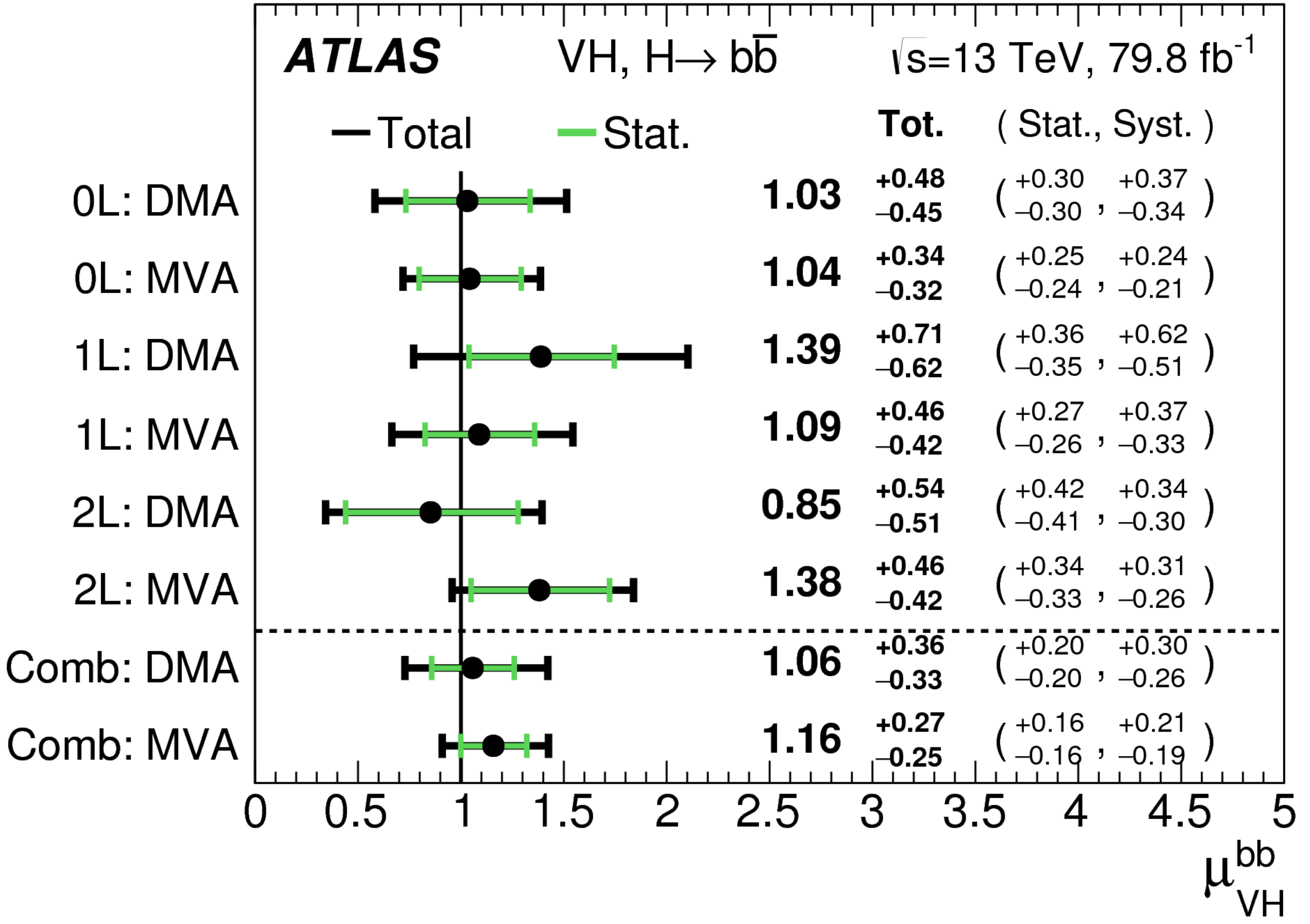
VH, H→bb Run 1 and Run 2 combination

The measured signal strength of the Higgs boson for mass at 125 GeV for the WH and ZH processes and their combination.



The measured signal strength in individual channels

MVA analysis: the compatibility probability of the signal strengths measured in the three lepton channels is 80%.



	Tot.	(Stat., Syst.)
0L: DMA	$1.03^{+0.48}_{-0.45}$	$(^{+0.30}_{-0.30}, ^{+0.37}_{-0.34})$
0L: MVA	$1.04^{+0.34}_{-0.32}$	$(^{+0.25}_{-0.24}, ^{+0.24}_{-0.21})$
1L: DMA	$1.39^{+0.71}_{-0.62}$	$(^{+0.36}_{-0.35}, ^{+0.62}_{-0.51})$
1L: MVA	$1.09^{+0.46}_{-0.42}$	$(^{+0.27}_{-0.26}, ^{+0.37}_{-0.33})$
2L: DMA	$0.85^{+0.54}_{-0.51}$	$(^{+0.42}_{-0.41}, ^{+0.34}_{-0.30})$
2L: MVA	$1.38^{+0.46}_{-0.42}$	$(^{+0.34}_{-0.33}, ^{+0.31}_{-0.26})$
Comb: DMA	$1.06^{+0.36}_{-0.33}$	$(^{+0.20}_{-0.20}, ^{+0.30}_{-0.26})$
Comb: MVA	$1.16^{+0.27}_{-0.25}$	$(^{+0.16}_{-0.16}, ^{+0.21}_{-0.19})$

H→bb combination in Run 1 and Run 2

The compatibility of the individual signal strengths is 54%.