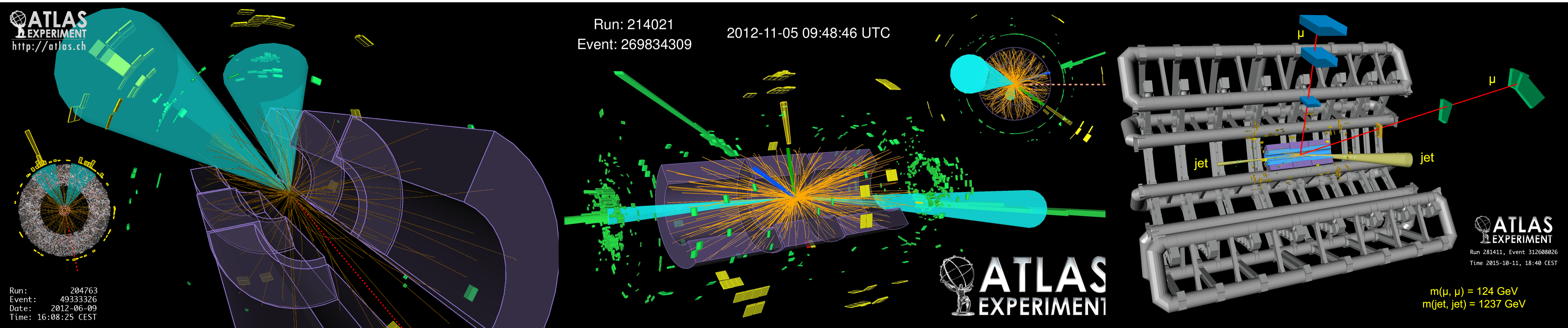
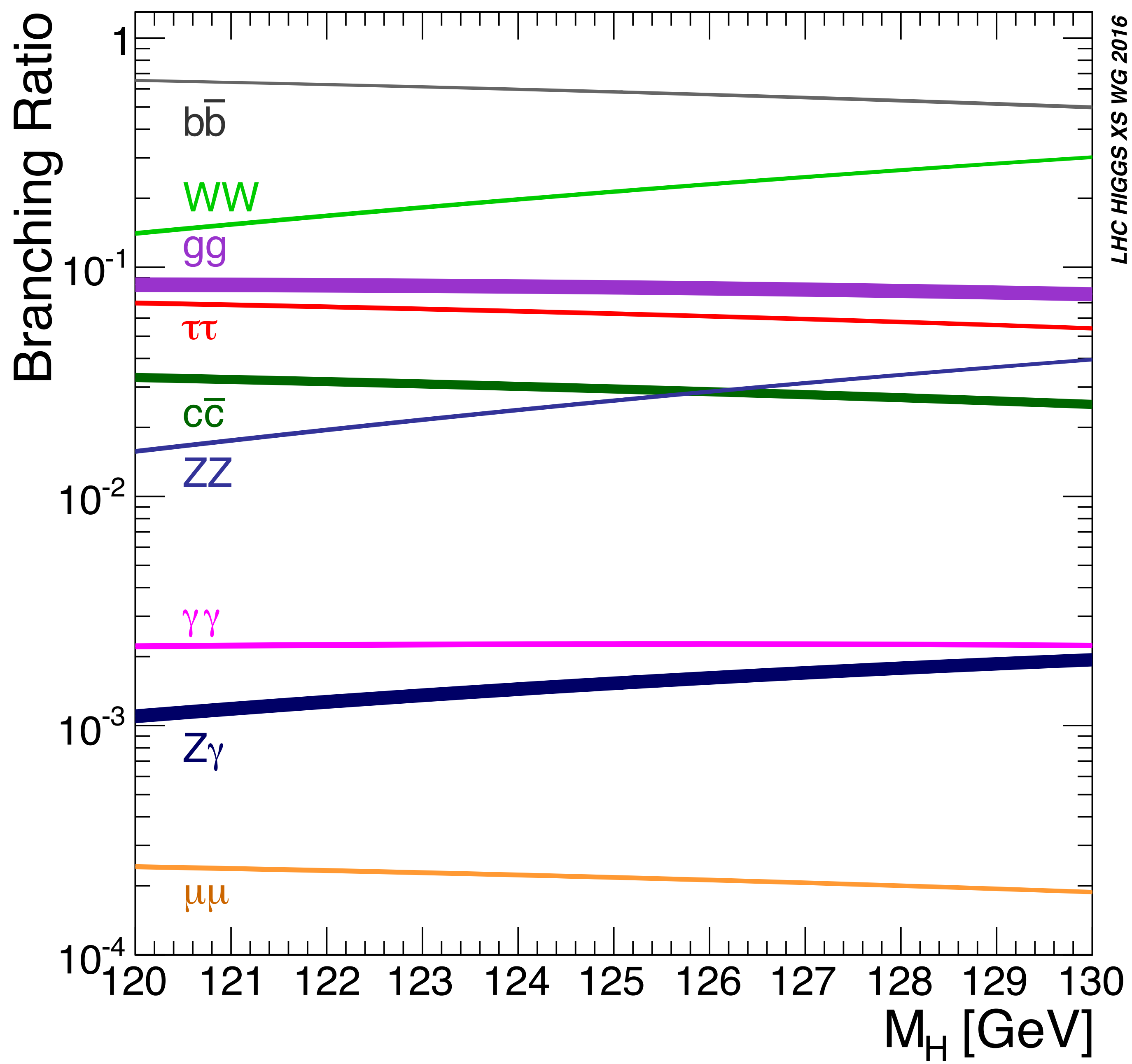
Higgs measurements in bb, ττ and μμ decay channels with ATLAS

Quentin Buat (CERN) on behalf of the ATLAS collaboration - SUSY 2017



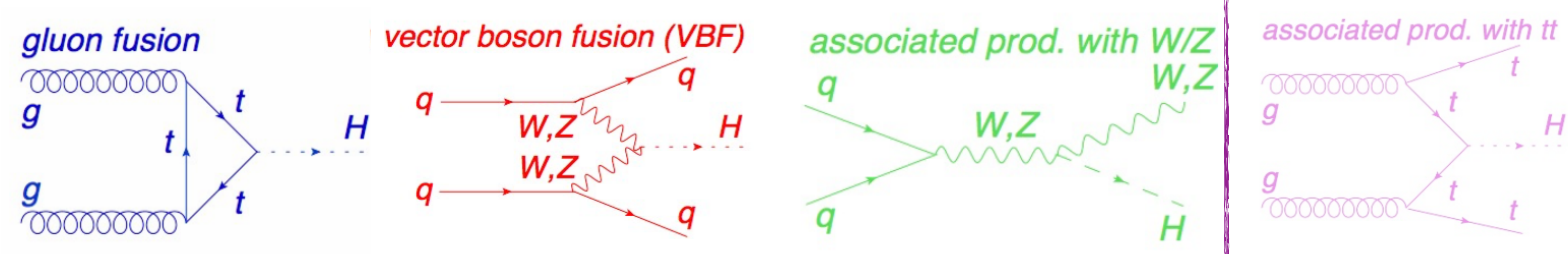
Introduction

- Higgs boson discovery driven by the bosonic final states
- bb, ττ and μμ decay channels are a direct probe of the Yukawa mechanism
- bb is the largest branching ratio:
    - drives the uncertainty on the total width



Higgs → fermions

86% | 7% | 5% | 0.5%



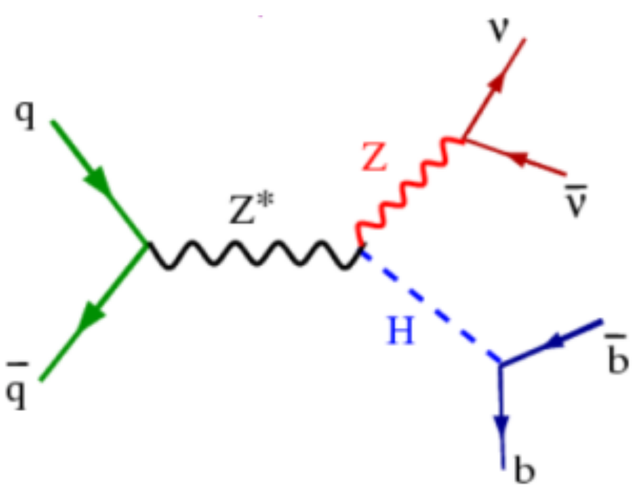
Decay	bb	ττ	μμ
Production mode probed	VH, VBF	ggH, VBF, VH	ggH, VBF
Dataset	Run1, Run2	Run1	Run1, Run2
Measurements	Couplings	Couplings, CP studies	Couplings (sensitivity)

Dedicated talk by V. Kostyukhin

VH→bb: selection

https://arxiv.org/abs/1708.03299, submitted to JHEP

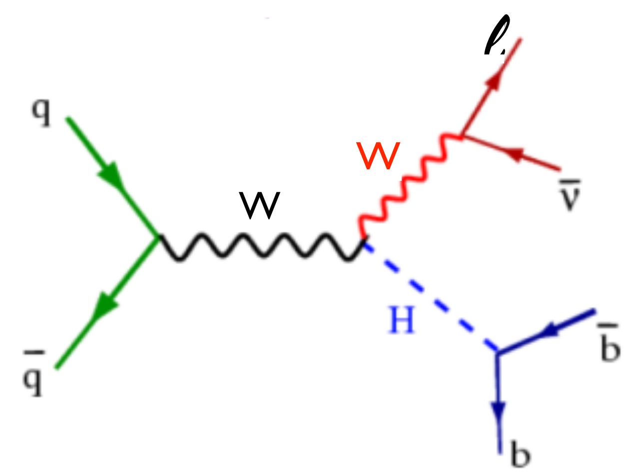
0 lepton



$$\mathrm{MET} > 150 \ \mathrm{GeV}$$

(+ additional criteria to suppress multi-jet)

1 lepton

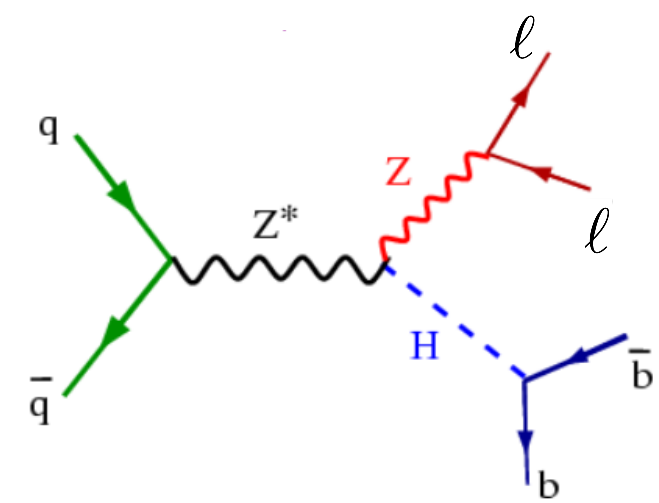


$$p_{\mathrm{T}}\,(\ell\nu) > 150 \ \mathrm{GeV}$$

Tightly isolated lepton

MET > 30 GeV in ele. channel)

2 leptons



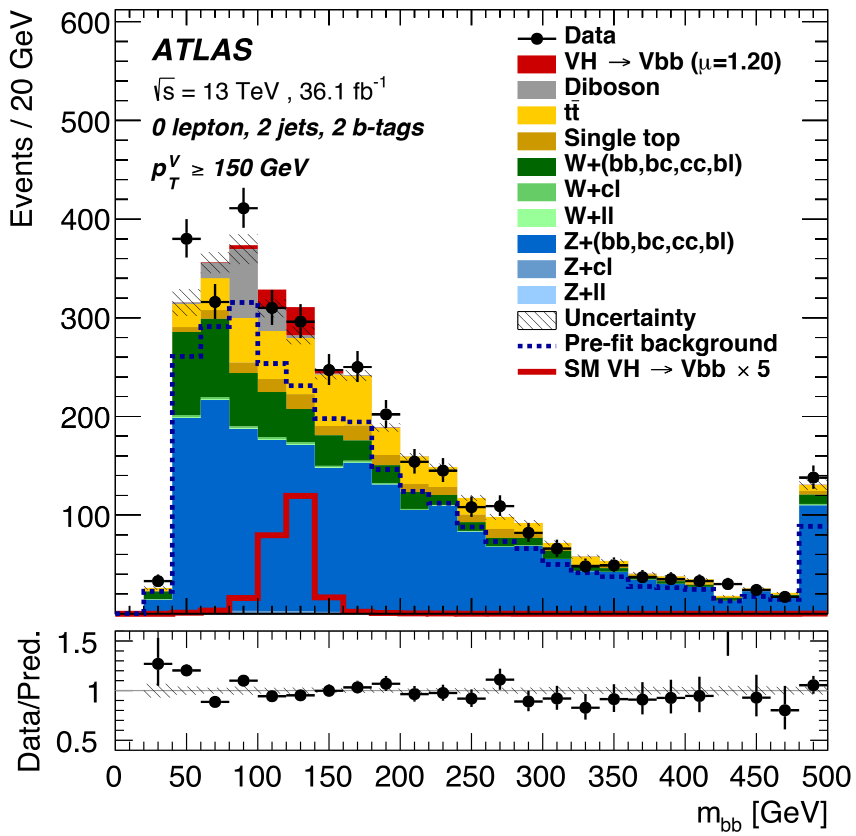
$$|\mathrm{m}_{\ell\ell} - 91 \ \mathrm{GeV}| < 10 \ \mathrm{GeV}$$

$$p_{\mathrm{T}}\,(\ell\ell) > 75 \ \mathrm{GeV}$$

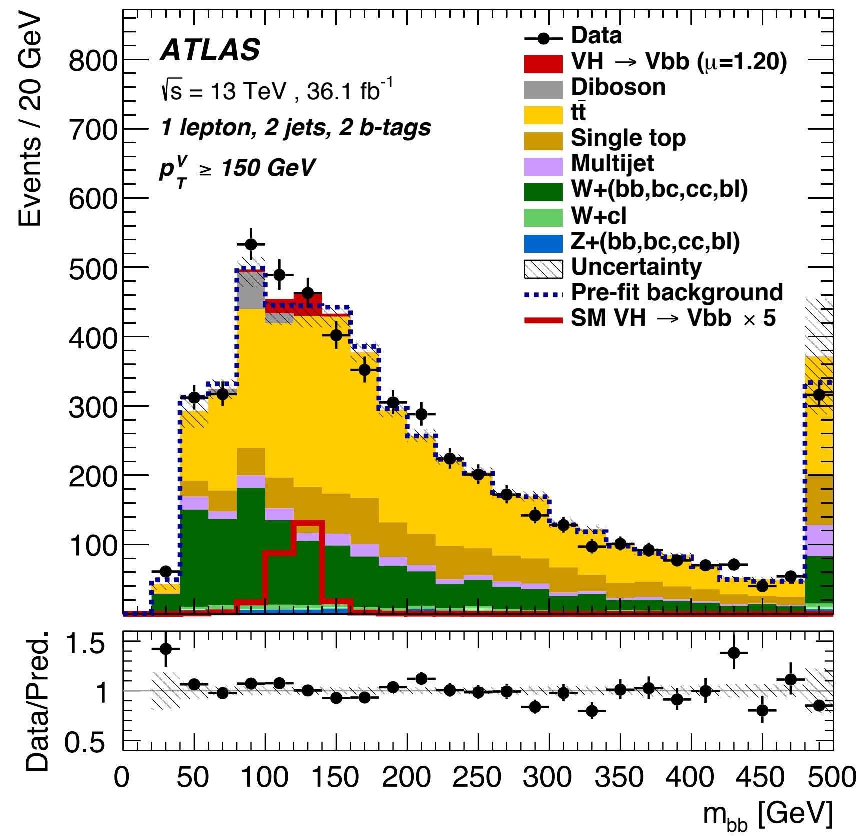
- Channels denoted by the number of charged leptons (e or μ)
- Trigger based on single lepton and MET
- 2 b-tagged jets with (>45, >20) GeV
- Exactly 2 or 3 jets (0,1-lepton), 2 or ≥3 jets (2-lepton)

VH→bb: backgrounds

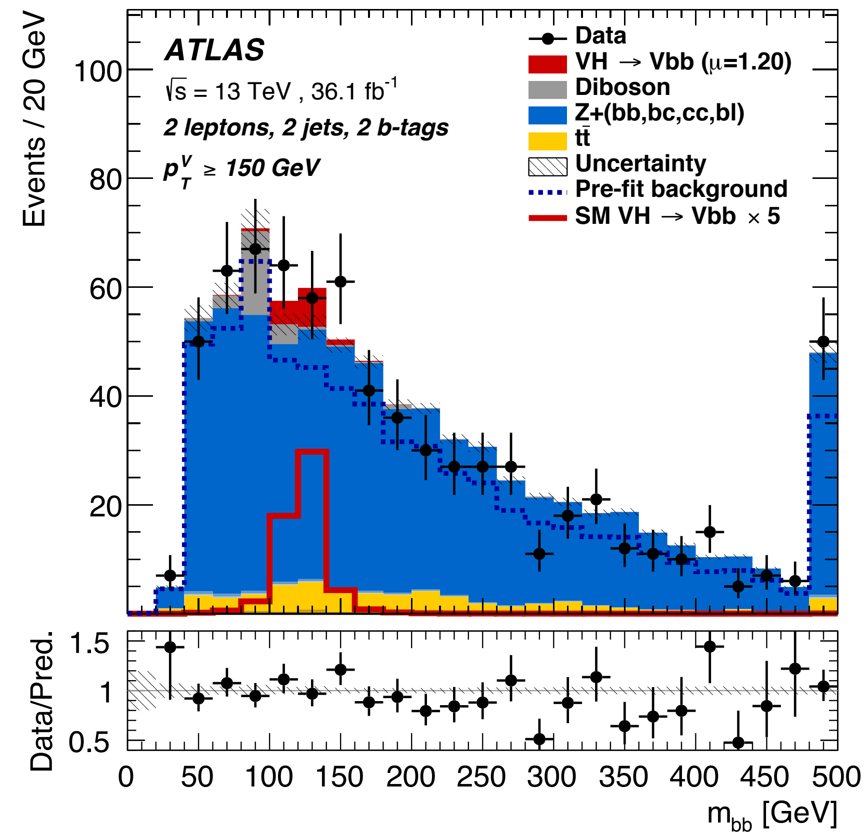
0 lepton



1 lepton



2 leptons



- Dominant backgrounds **W+jets**, **Z+jets**, **top** estimated from simulation
- Small multijet background (5%) in the 1-lepton channel: data driven
- Resonant VZ → bb used to validate the analysis

VH→bb: signal extraction

- Multivariate analysis employing BDTs
  - Exploit the full kinematic of the event
- Events categorized in 8 signal regions and 6 control regions
- Likelihood fit designed to extract the signal strength as well as the normalizations of the main backgrounds

BDT input variables

Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	$\times$	$\times$
E_T^{miss}	$\times$	$\times$	$\times$
$p_T^{b_1}$	$\times$	$\times$	$\times$
$p_T^{b_2}$	$\times$	$\times$	$\times$
m_{bb}	$\times$	$\times$	$\times$
$\Delta R(\vec{b}_1, \vec{b}_2)$	$\times$	$\times$	$\times$
$\|\Delta\eta(\vec{b}_1, \vec{b}_2)\|$	$\times$		
$\Delta\phi(\vec{V}, \vec{bb})$	$\times$	$\times$	$\times$
$\|\Delta\eta(\vec{V}, \vec{bb})\|$			$\times$
m_{eff}	$\times$		
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		$\times$	
m_T^W		$\times$	
$m_{\ell\ell}$			$\times$
m_{top}		$\times$	
$\|\Delta Y(\vec{V}, \vec{bb})\|$		$\times$	
	Only in 3-jet events		
$p_T^{jet_3}$	$\times$	$\times$	$\times$
m_{bbj}	$\times$	$\times$	$\times$

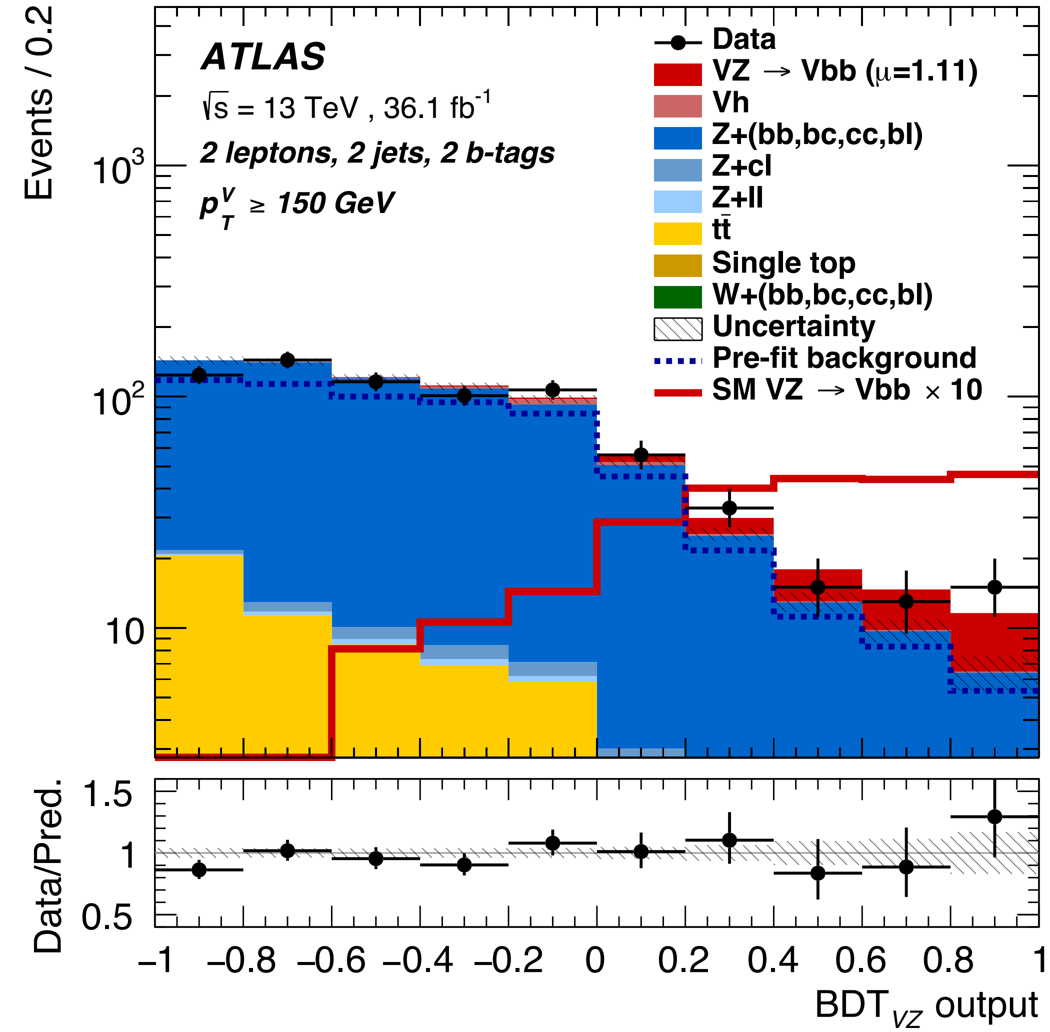
Channel	SR/CR	Categories			
		75 GeV $< p_T^V <$ 150 GeV		$p_T^V >$ 150 GeV	
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	-	-	BDT	BDT
1-lepton	SR	-	-	BDT	BDT
2-lepton	SR	BDT	BDT	BDT	BDT
1-lepton	W + HF CR	-	-	Yield	Yield
2-lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield	m_{bb}

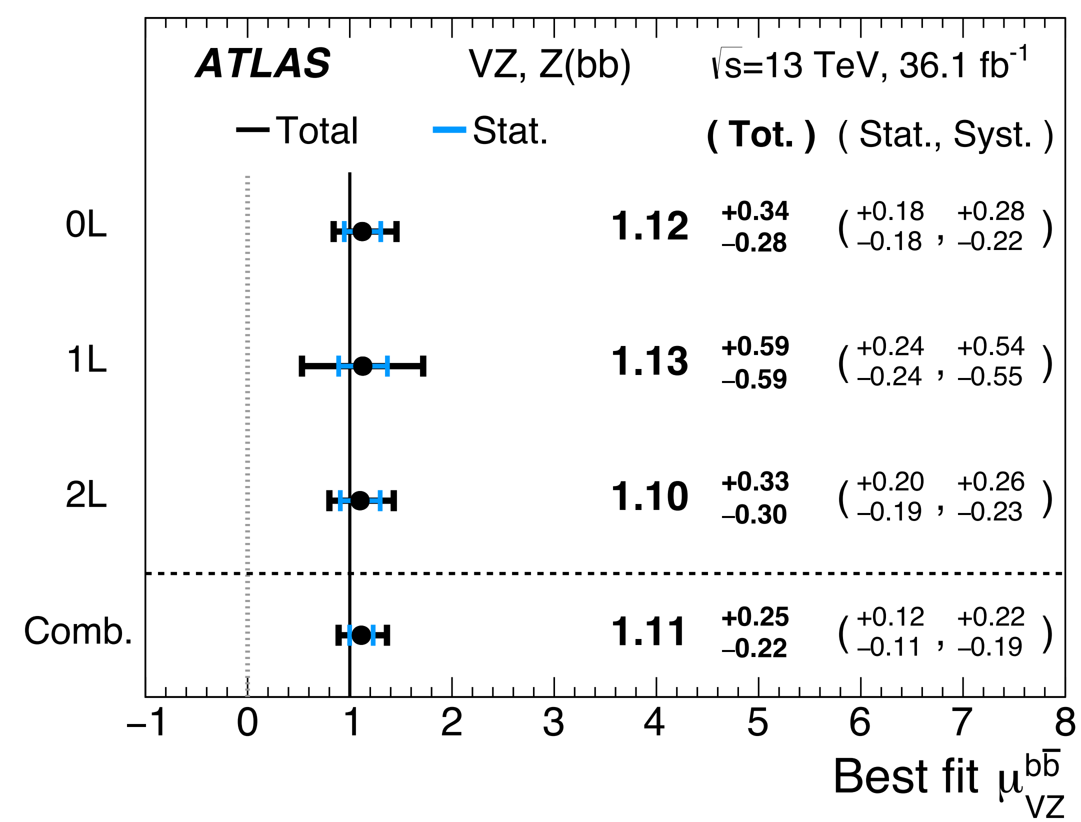
constrain W+HF

constrain Top

VZ→bb: results

- Exercise the analysis on the well-established SM WZ, ZZ production
- 5.8σ observed significance
- Compatible with SM expectation within 1σ
- This validates the BDT analysis

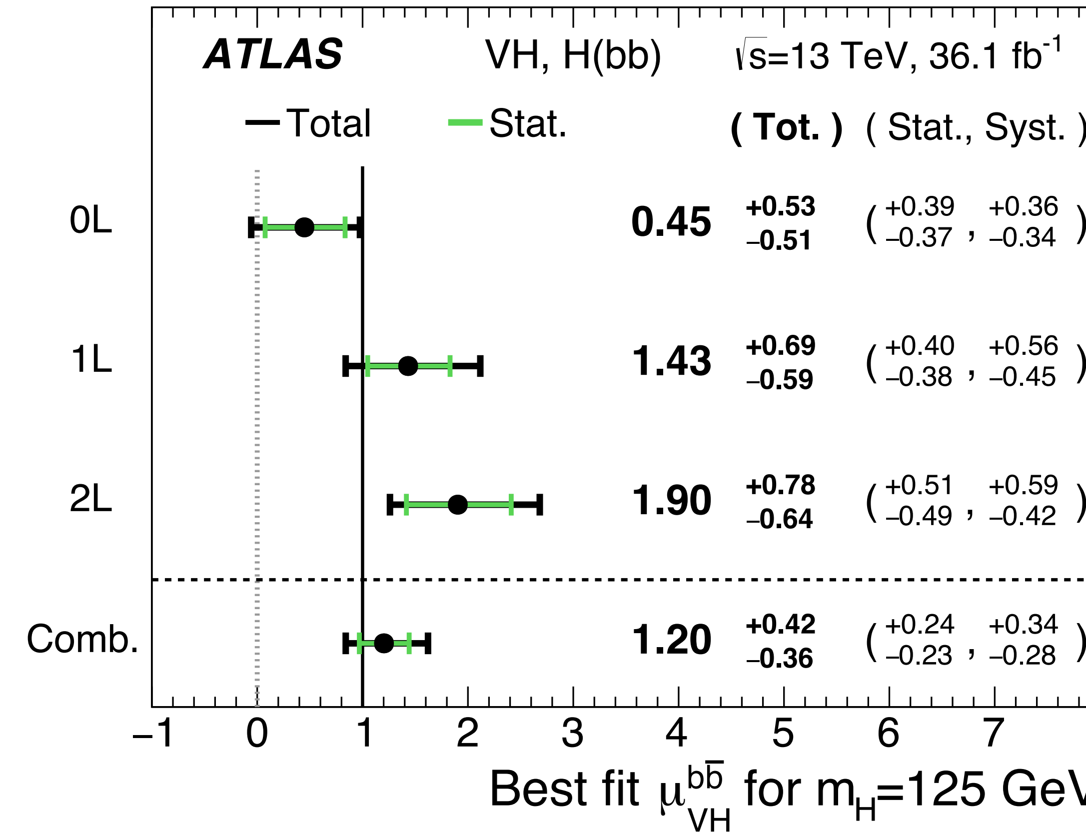


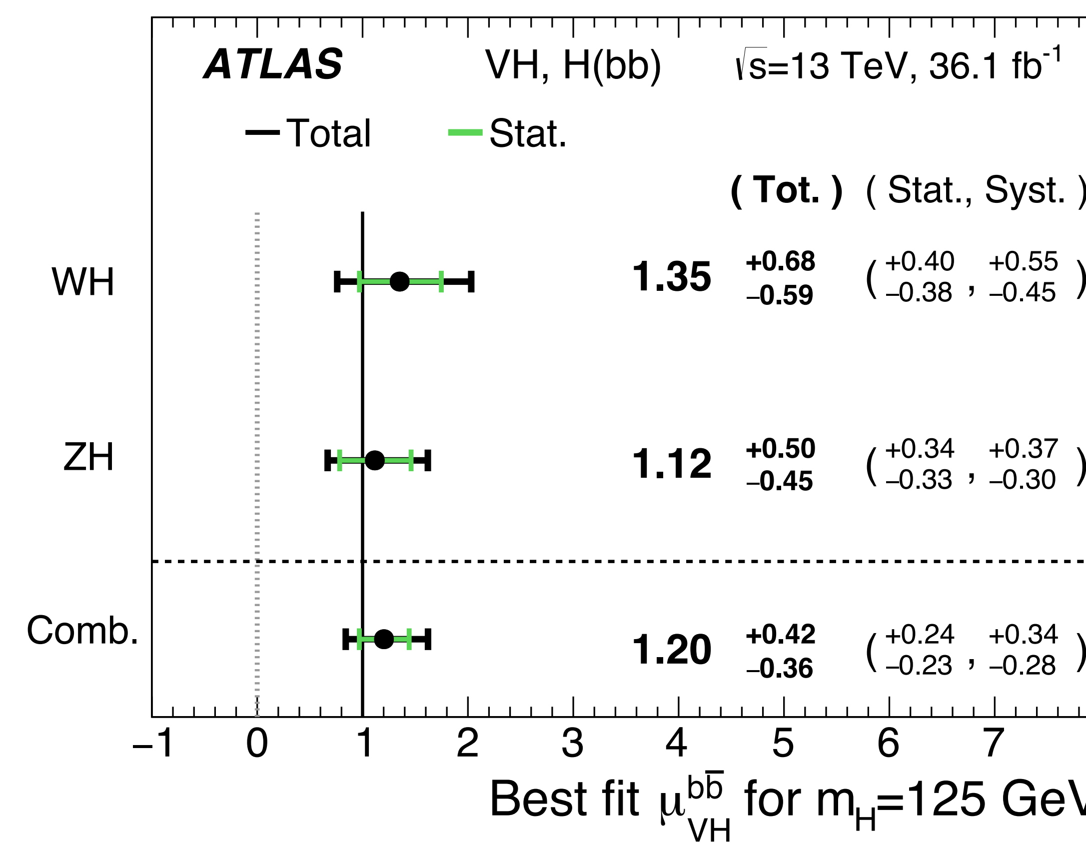


VH→bb: results

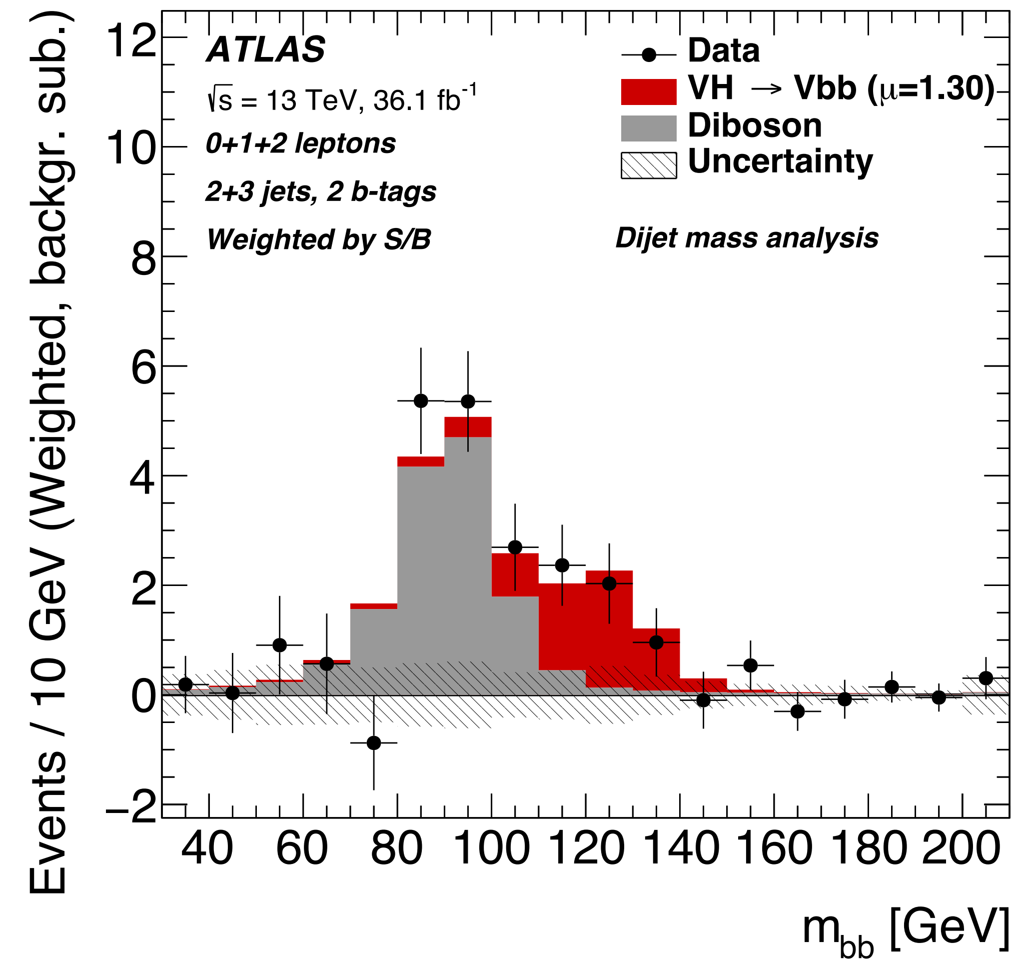
- 3.5σ (3.0σ) observed (expected) significance
- Fair compatibility across channels
- Stronger signal in ZH than WH
- Dominant systematic uncertainties:

Source	σ_μ (%)
Signal theory	17
MC statistics	13
Top modelling	8
Z+jets and W+jets	7 (each)
b-tagging	10

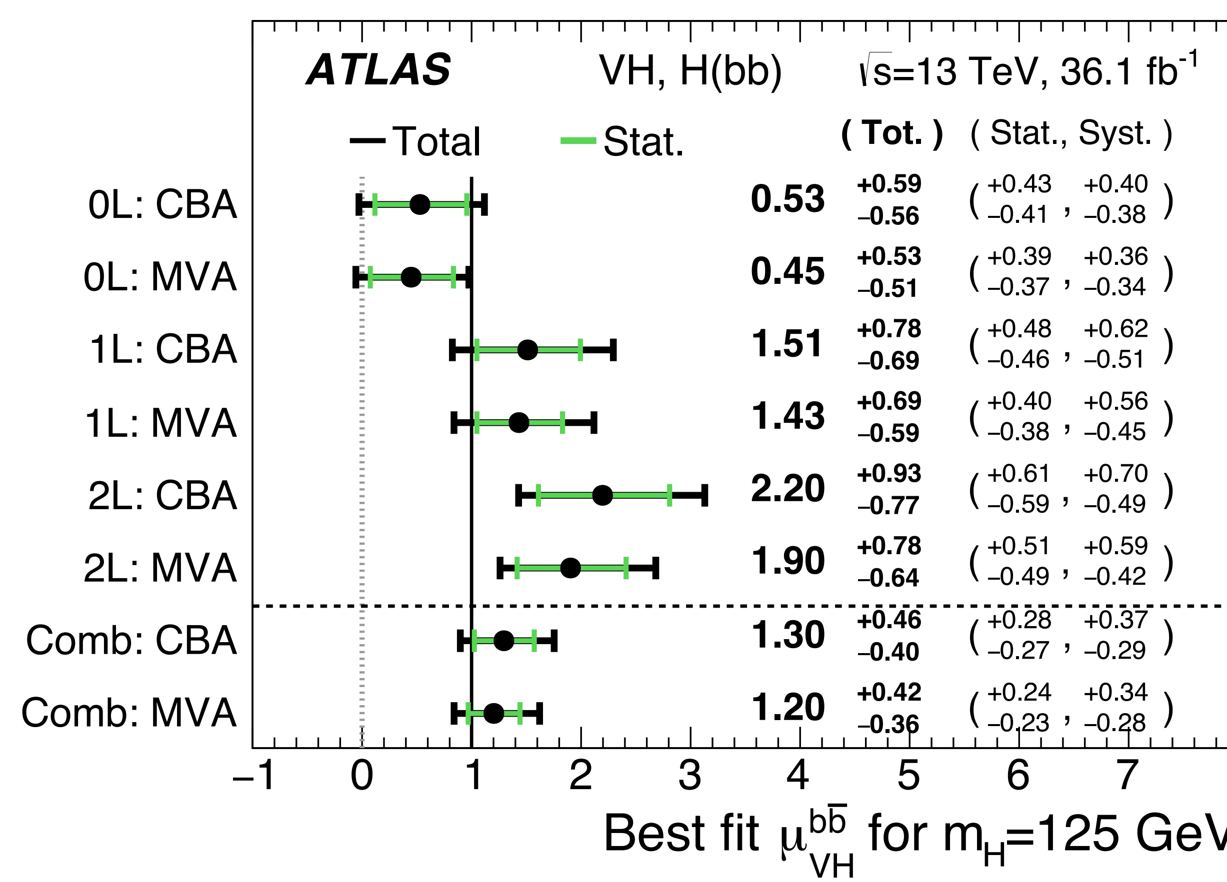




VH→bb: results

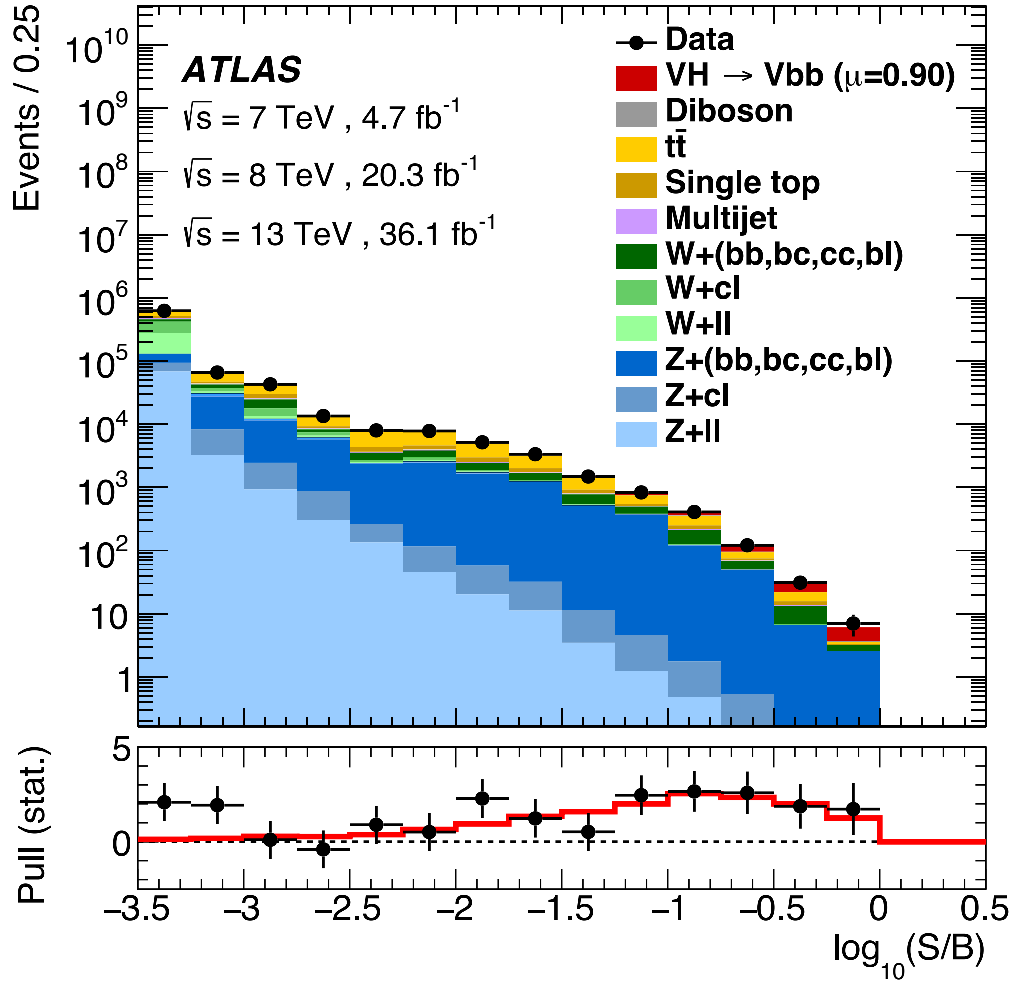


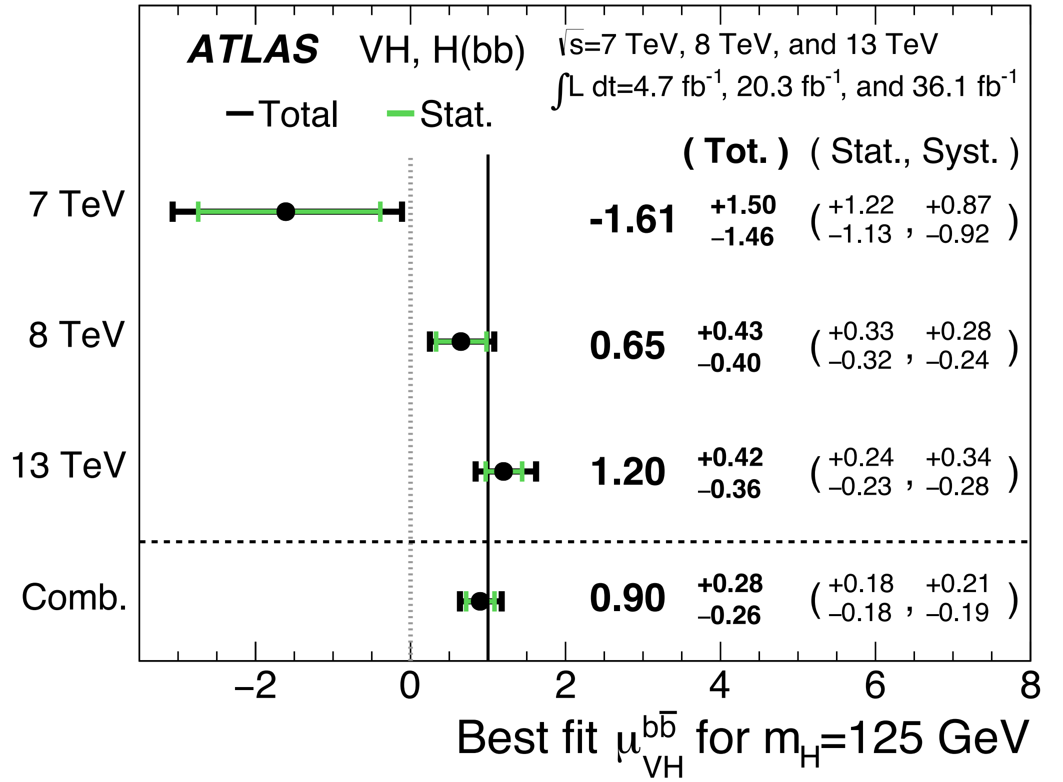
- Cross check analysis with the m_{bb} variable
- 3.5σ (2.8σ) observed (expected) significance
- Very good agreement with the BDT analysis



VH→bb: Run1 & Run2

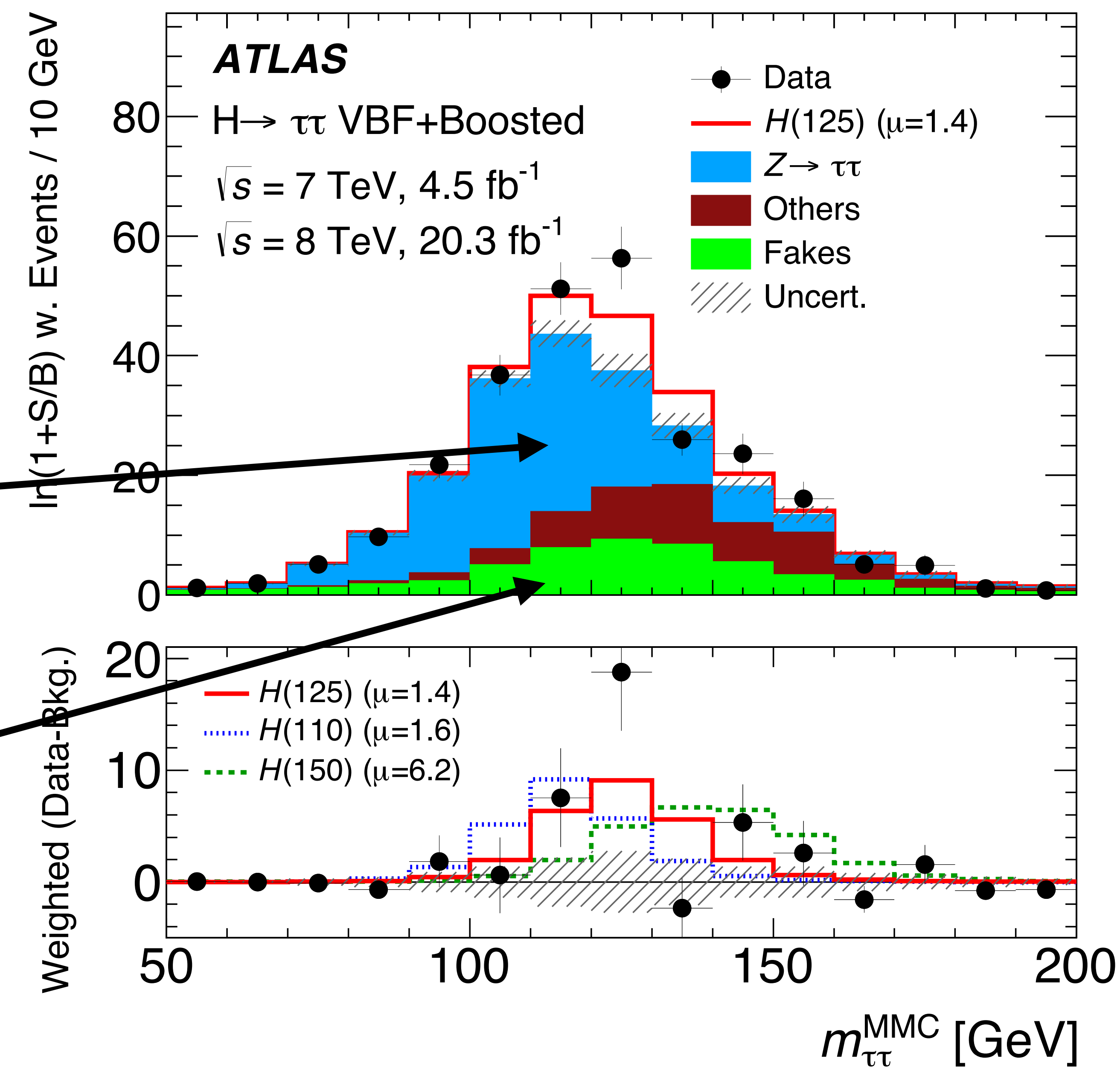
- Combining Run1 and Run2:
  - 3.6σ (4.0σ) observed (expected) significance
- ATLAS established evidence for Higgs decay to a pair of b-quarks!





H→ττ: analysis strategy

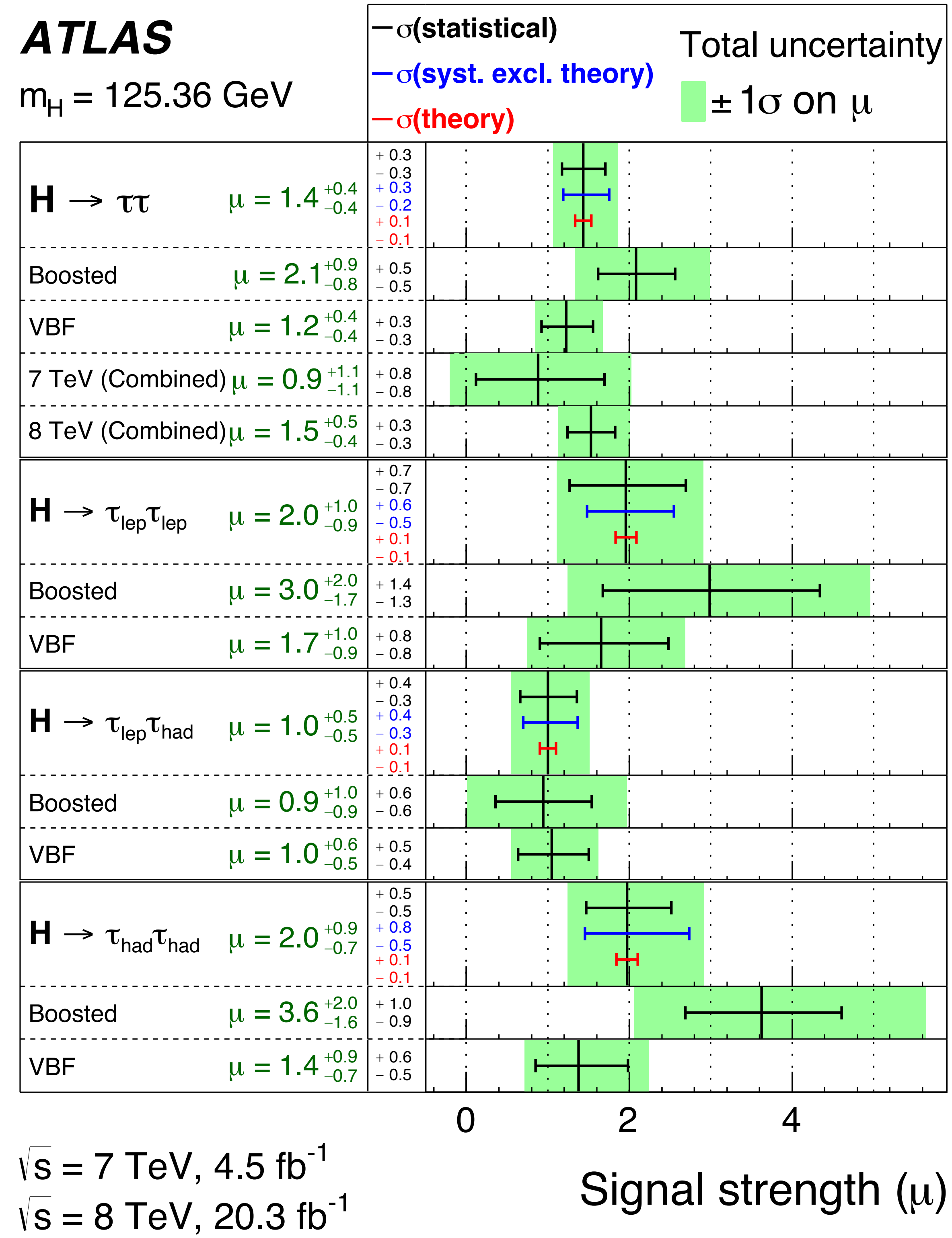
- Exploit all the tau decay channels
- Analysis designed to target VBF and Boosted regime
  - VBF: 2 high-p_T jets with high angular separation)
  - Boosted: $p_T(H) > 100$ GeV
- Dominant background: Z→ττ
  - Estimated using Z→μμ data with embedded simulated tau decays
- Large contribution from W→lv + jets and QCD:
  - Data driven estimates
- Missing Mass Calculator: likelihood-based estimate of the mass of the ditau system



H→ττ: results

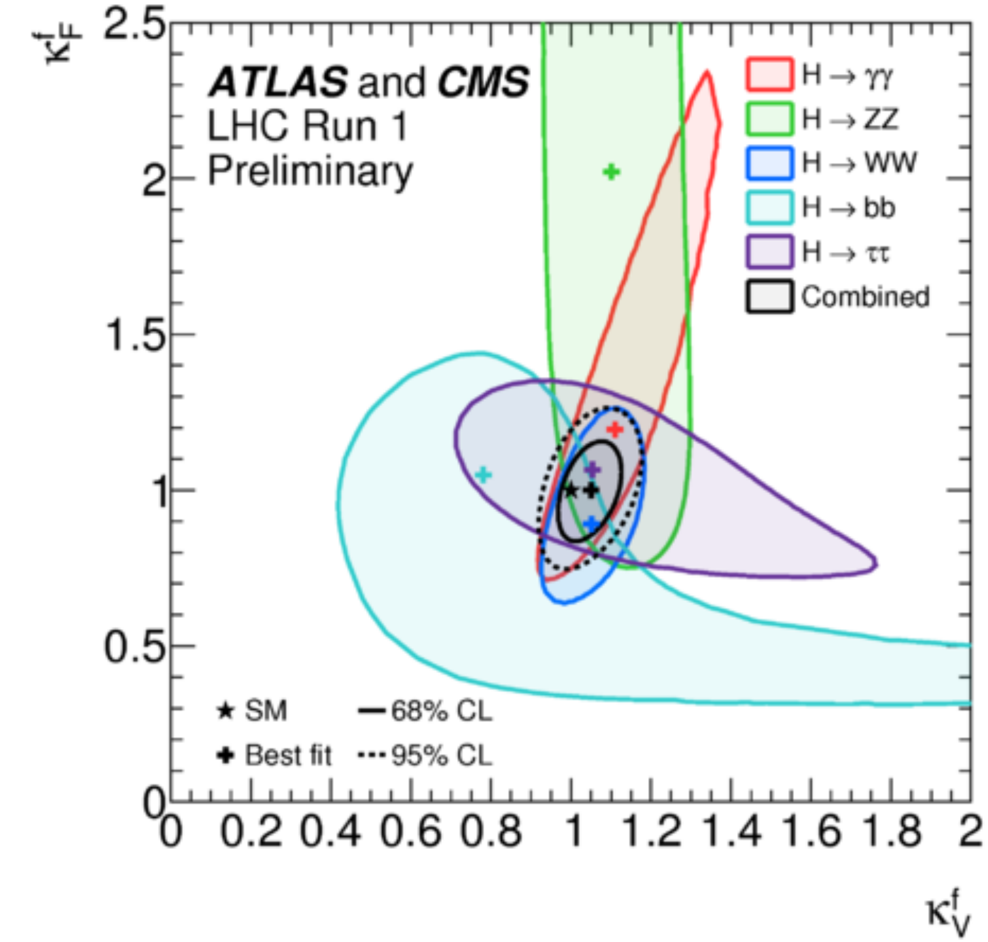
- 4.5σ (3.6σ) observed (expected) significance
- Very strong signal in the VBF categories
- Dominant systematic uncertainties:

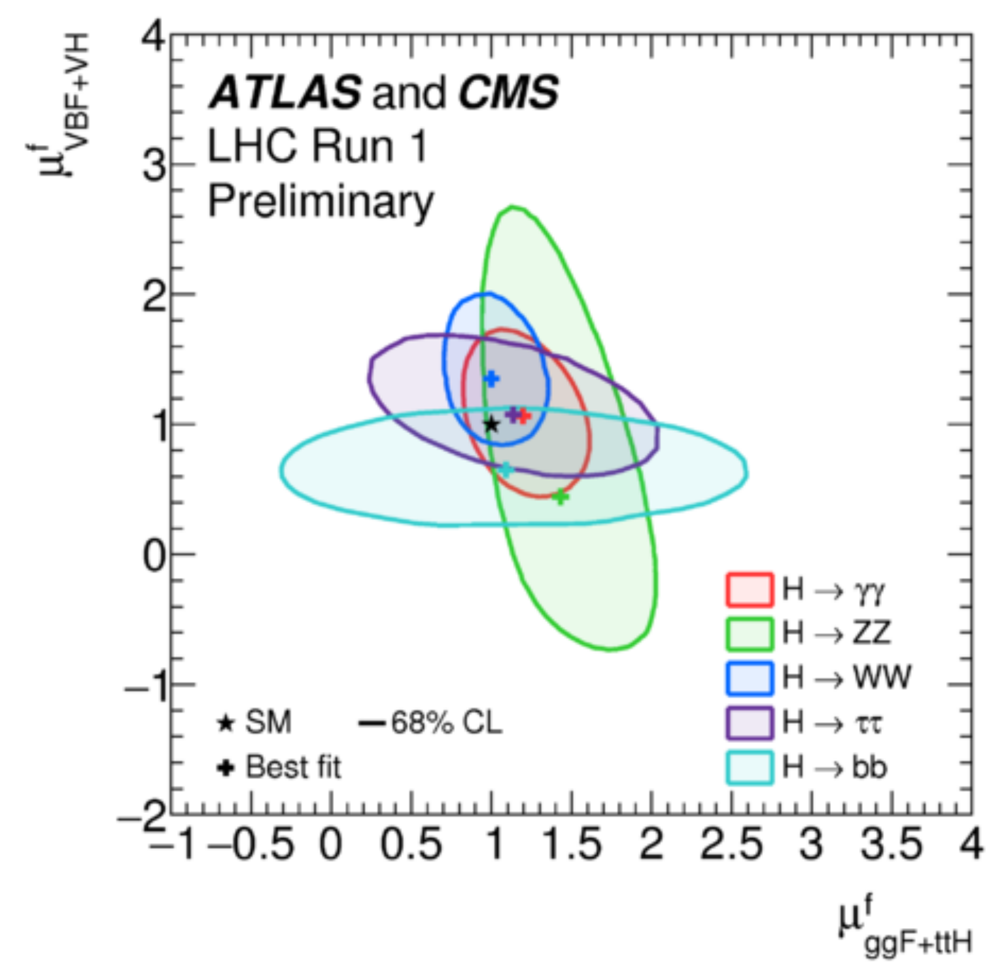
Source	σ_μ (%)
Jet energy scale	13
Back. normalization	12
MC and CR statistics	10
tau energy scale	7



H→ττ: ATLAS+CMS

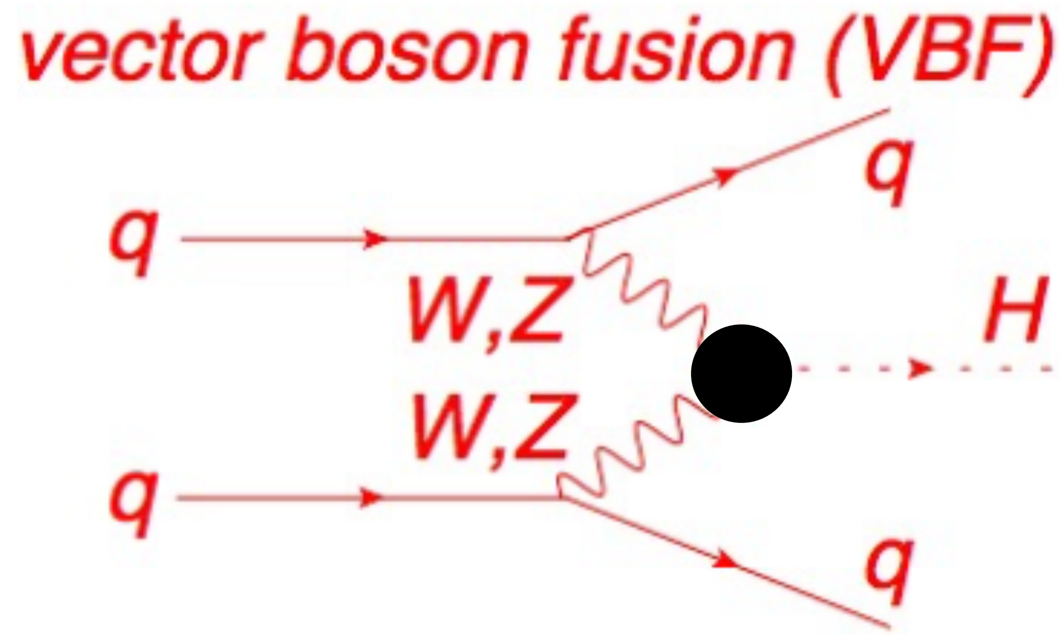
- ATLAS + CMS Run1 combination
- Combining with CMS, claim discovery (>5σ) of the tau coupling to the 125 GeV Higgs
- H→ττ brings strong constraints on k_F
- Similar constraint to H→WW to the VBF production mode.



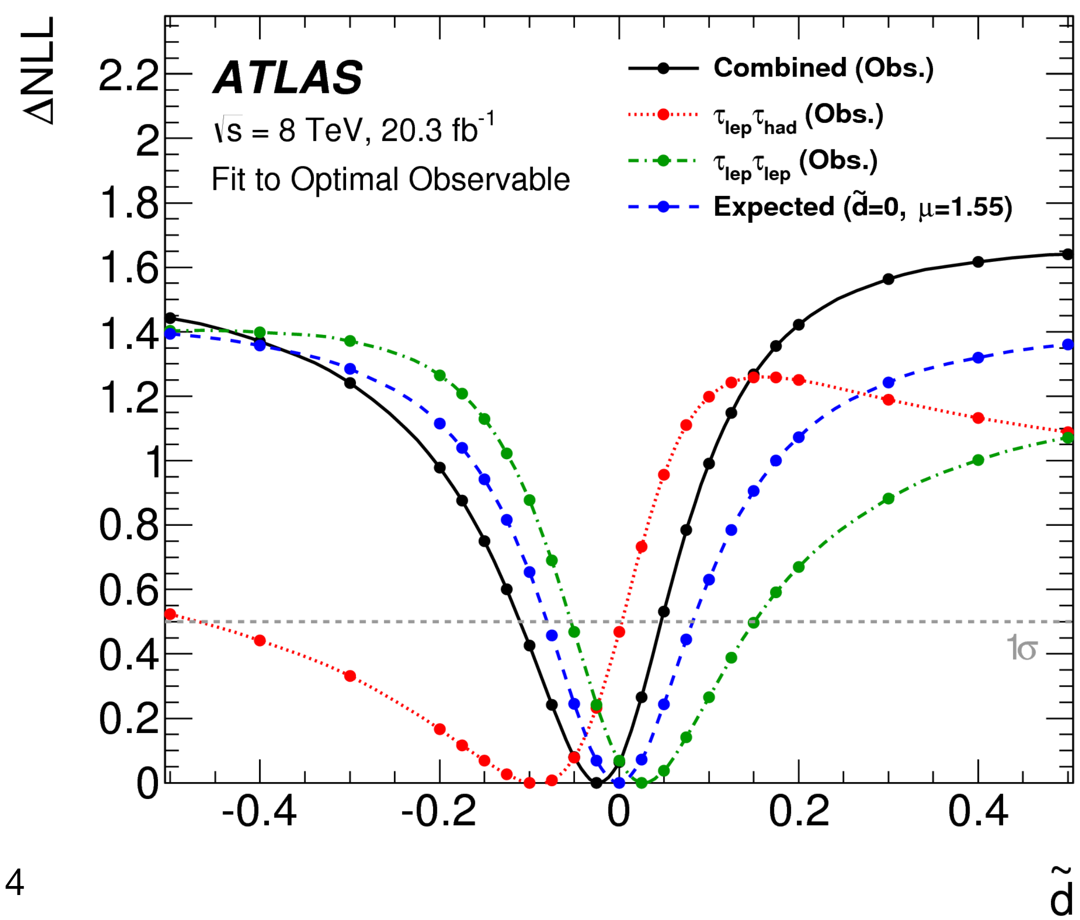


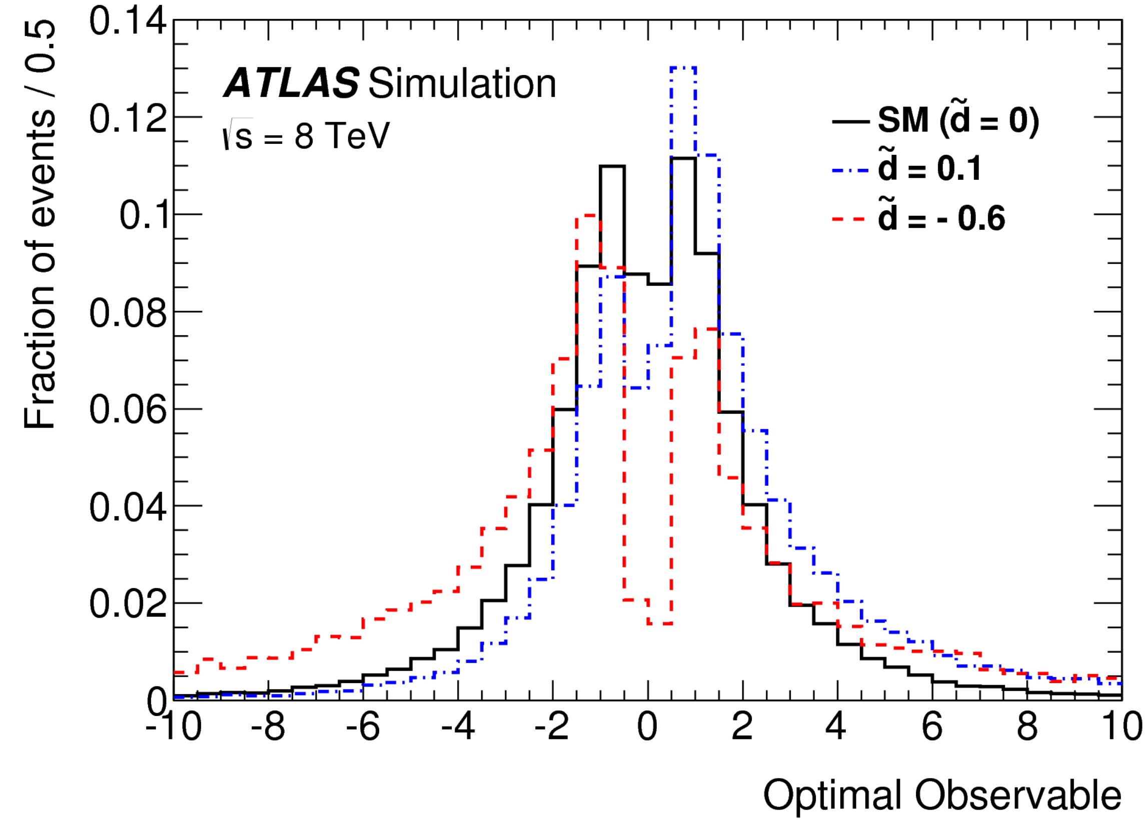
H→ττ: VBF CP

- Select events with high BDT_{VBF} score from the main analysis
- Use optimal observable to differentiate CP hypothesis
- Describe all CP-violating effects through a single parameter: d~
- d~ in [-0.11, 0.05] at 68% CL



$$\text{Optimal Observable} = \frac{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}$$



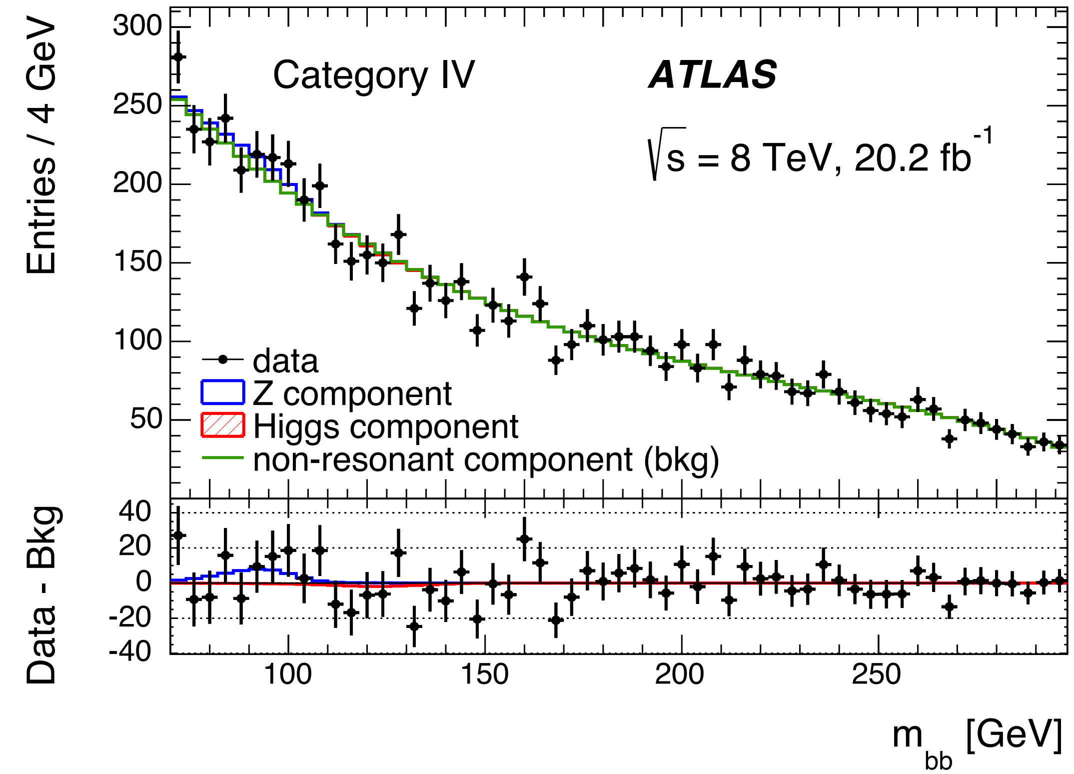


bb, ττ: completing the puzzle

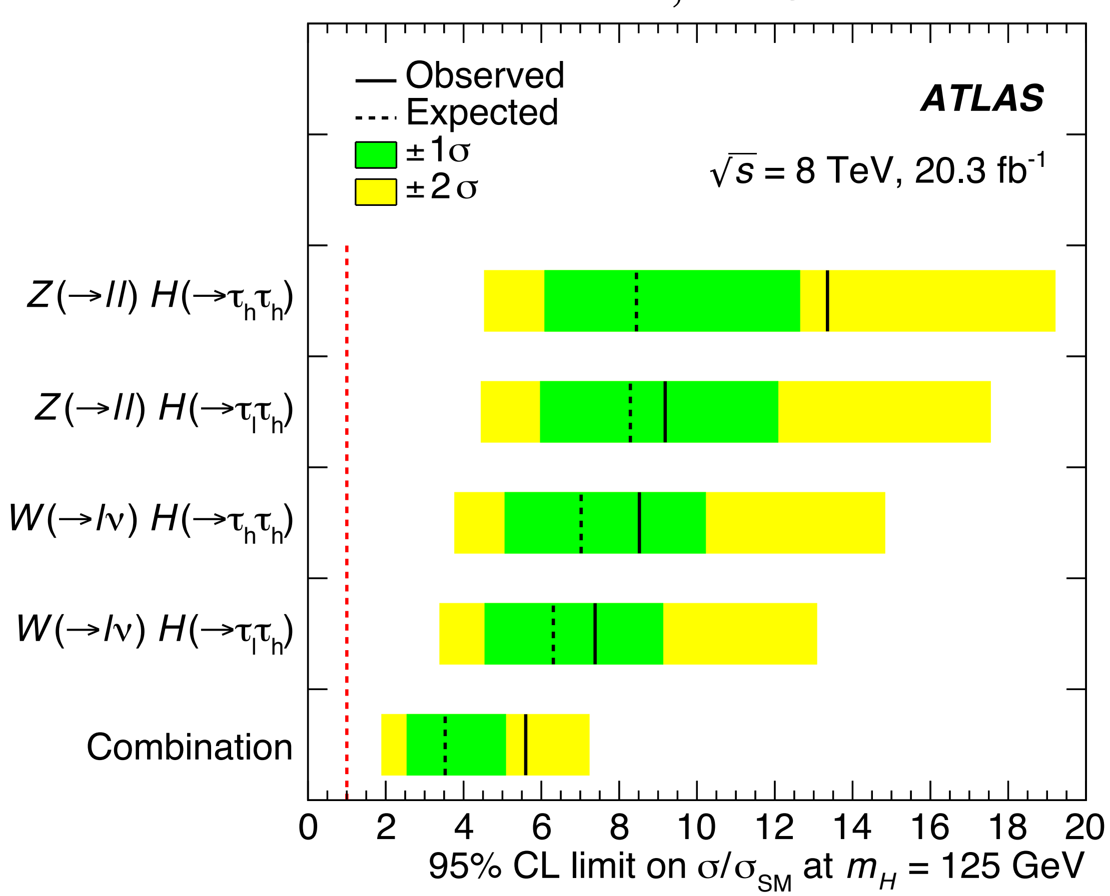
- Exploring other harder production modes:

	Limit on σ/σ_{SM} Obs.	Limit on σ/σ_{SM} Exp.	Best fit μ
VH→ττ	5.6	3.5	2.3 +/- 1.6
VBF H→bb	4.4	5.4	-0.8 +/- 2.3
VBF+γ H→bb	4.0	6.0	-3.9 +/- 2.8

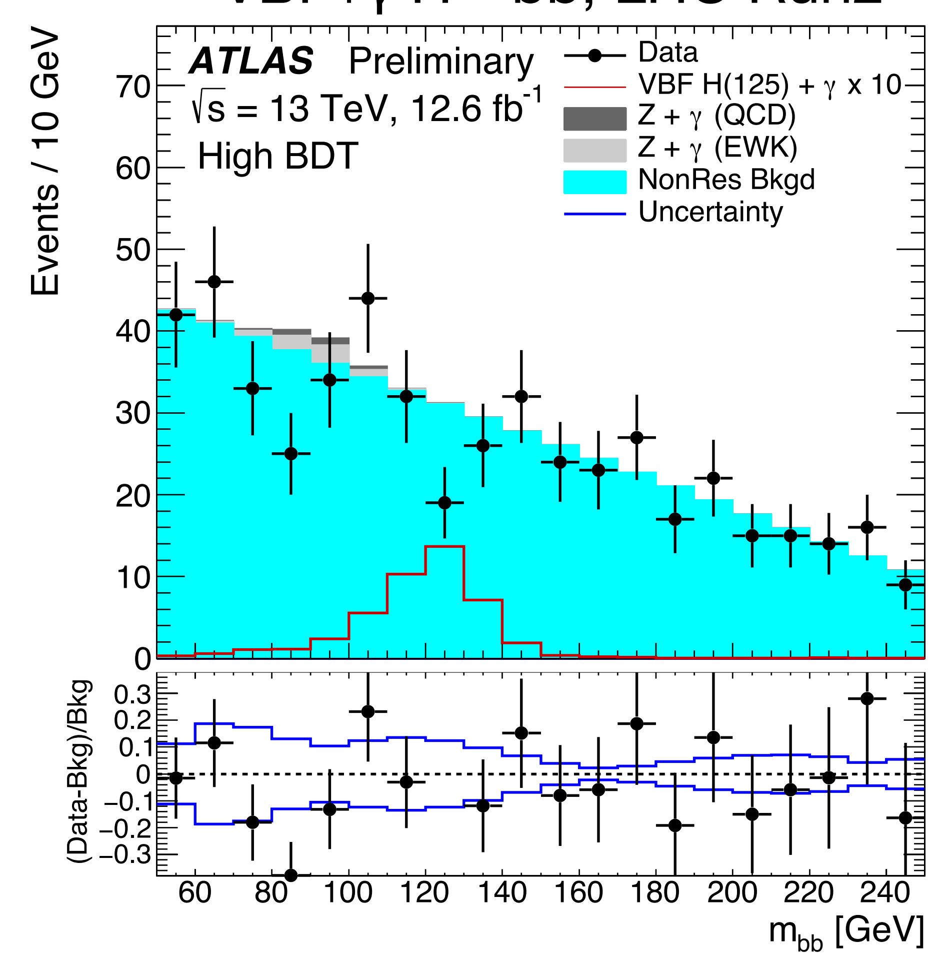
VBF H→bb, LHC Run1



VH→ττ, LHC Run1

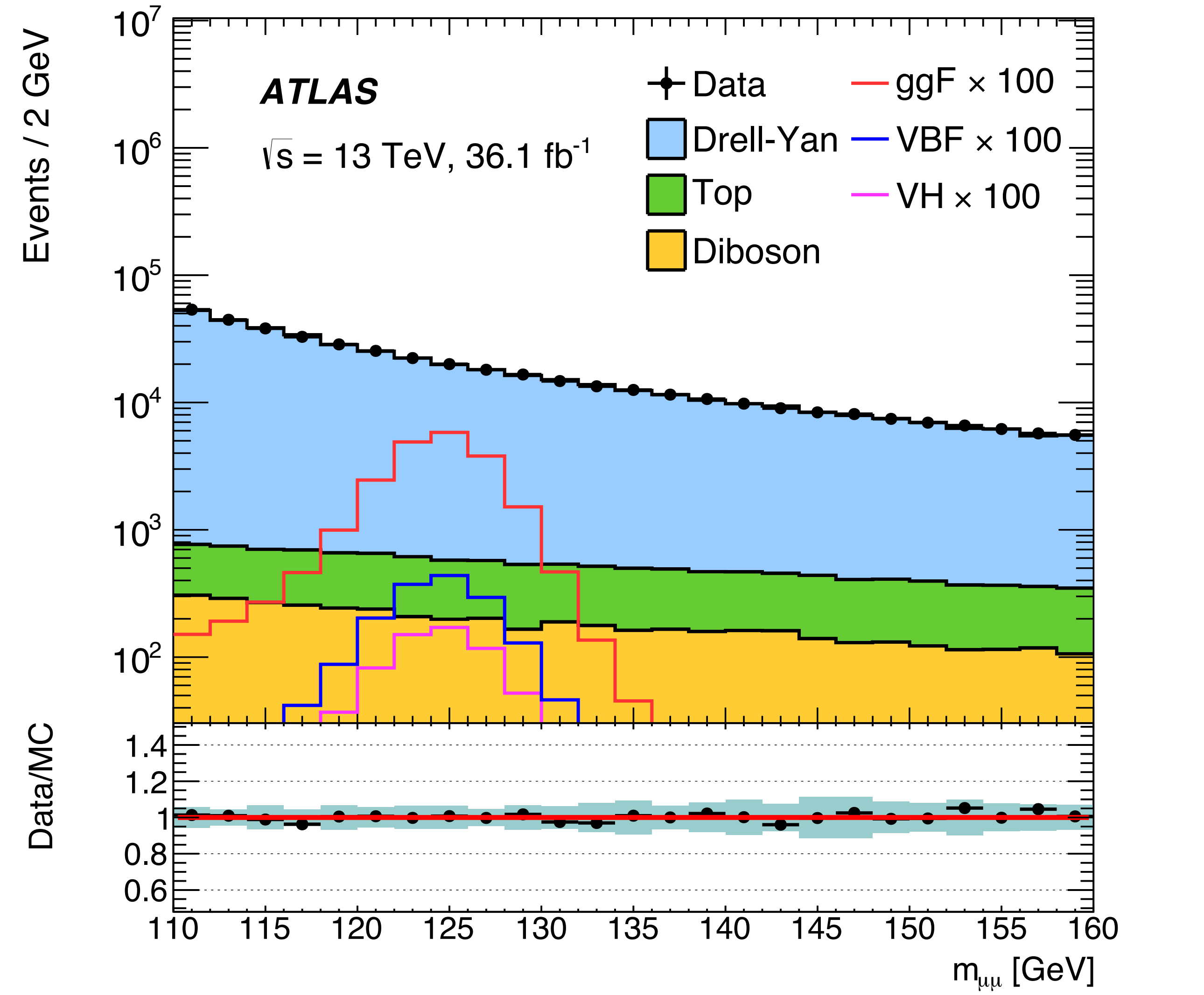


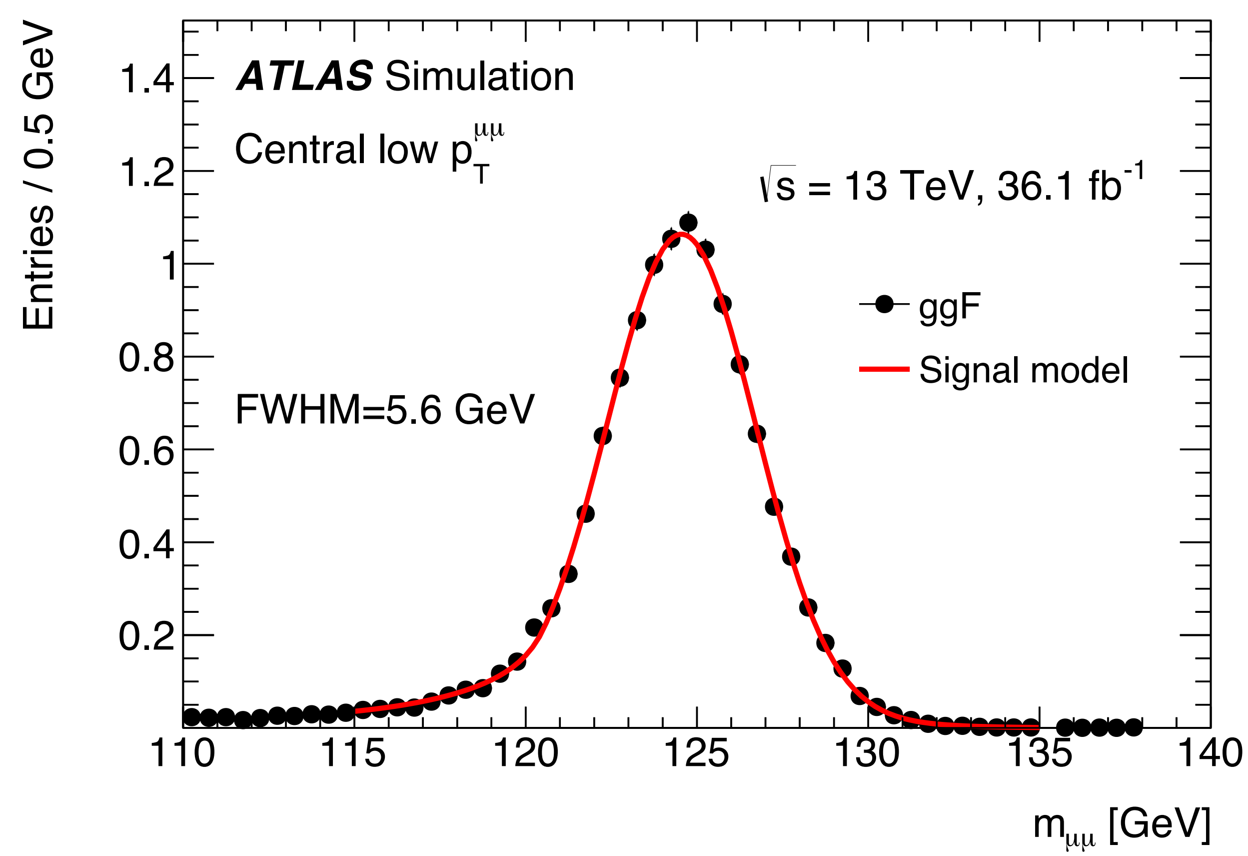
VBF+γ H→bb, LHC Run2



H→μμ: strategy

- Two isolated muons satisfying $110 < m_{\mu\mu}$ [GeV] < 160
- Background parameterised with a functional form
- Signal extraction using a binned likelihood fit
- Excellent mass resolution!
- but… tiny signal buried under overwhelming Drell-Yan production

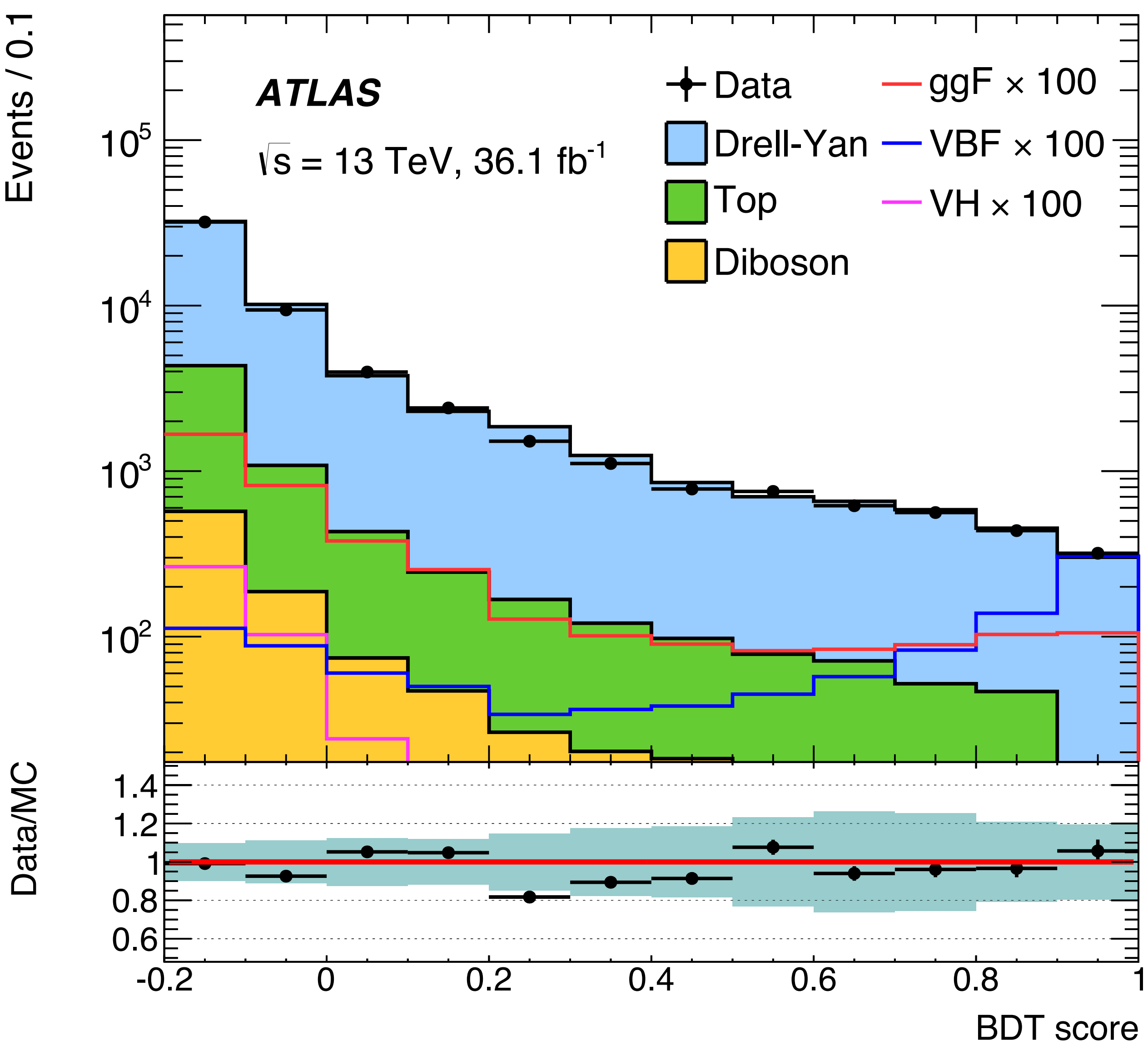




H→μμ: results

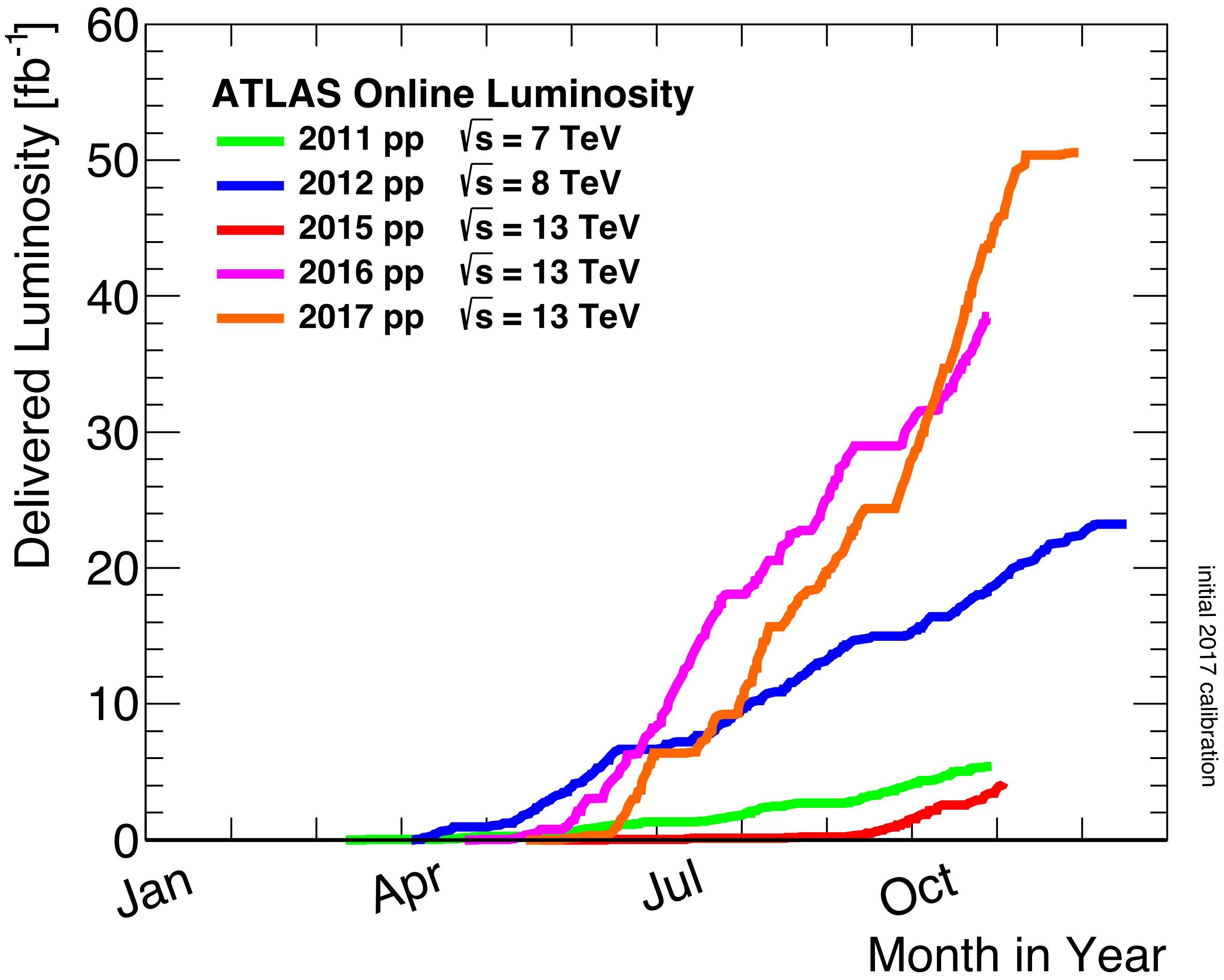
	S	B	$S/\sqrt{B}$	FWHM	Data
Central low $p_{\mathrm{T}}^{\mu\mu}$	11	8000	0.12	5.6 GeV	7885
Non-central low $p_{\mathrm{T}}^{\mu\mu}$	32	38000	0.16	7.0 GeV	38777
Central medium $p_{\mathrm{T}}^{\mu\mu}$	23	6400	0.29	5.7 GeV	6585
Non-central medium $p_{\mathrm{T}}^{\mu\mu}$	66	31000	0.37	7.1 GeV	31291
Central high $p_{\mathrm{T}}^{\mu\mu}$	16	3300	0.28	6.3 GeV	3160
Non-central high $p_{\mathrm{T}}^{\mu\mu}$	40	13000	0.35	7.7 GeV	12829
VBF loose	3.4	260	0.21	7.6 GeV	274
VBF tight	3.4	78	0.38	7.5 GeV	79

- Event categorization
  - Designed a multivariate classifier targeting VBF production mode
  - Achieved a $S/\sqrt{B} = 0.37$ in the VBF tight region
- Observed limit: 3 x SM expectation
- Combining with Run1:
  - Limit: 2.8 x SM expectation
  - $\mu_S = -0.1 \pm 1.4$
- Dominated by data statistics
- ATLAS + CMS combination of H→μμ may reach the standard model sensitivity by the end of Run2!



Conclusions

- ATLAS firmly established the coupling of the Higgs boson
    - to b-quarks
    - to tau leptons
- Run2 data will shed the light on the fermion sector
    - (differential) cross-section measurements
    - CP studies (decay and VBF)
    - Establishment of the rare production modes
- ATLAS + CMS combination of H→μμ may reach the standard model sensitivity by the end of Run2!



References

Quentin Buat (CERN)

Analysis	Figures and tables	ArXiv	Journal
H→bb	https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2016-29/	https://arxiv.org/abs/1708.03299	submitted to JHEP
VBF H→bb	https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2014-12/	https://arxiv.org/abs/1606.02181	JHEP 11 (2016) 112
VBF+γ H→bb	https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-063/	https://cds.cern.ch/record/2206201	ATLAS-CONF-2016-063
H→ττ	https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-32/	https://arxiv.org/abs/1501.04943	JHEP04(2015)117
VBF H→ττ CP	https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2015-06/	https://arxiv.org/abs/1602.04516	EPJC76(2016)658
VH→ττ	https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2014-01/	https://arxiv.org/abs/1511.08352	PRD93,092005
H→μμ	https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2016-10/	https://arxiv.org/abs/1705.04582	PRL119(2017)051802
Run1 combination	https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2015-07/	https://arxiv.org/abs/1606.02266	JHEP08(2016)045

Additional material

VZ → bb: even selection table

Selection	0-lepton	1-lepton: e sub-channel	1-lepton: μ sub-channel	2-lepton
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 medium 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 or 3 jets			Exactly 2 or ≥ 3 jets
Jet p_{T}	> 20 GeV			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_{T}	> 45 GeV			
H_{T}	> 120 (2 jets), >150 GeV (3 jets)	–		–
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{\mathrm{jets}})]$	$> 20°$ (2 jets), $> 30°$ (3 jets)	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{bb})$	$> 120°$	–		–
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140°$	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{E}_{\mathrm{T,trk}}^{\mathrm{miss}})$	$< 90°$	–		–
p_{T}^{V} regions	> 150 GeV			(75, 150] GeV, > 150 GeV
Signal regions	✓	$m_{bb} \geq 75$ GeV or $m_{\mathrm{top}} \leq 225$ GeV		Same-flavour leptons Opposite-sign charge ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{\mathrm{top}} > 225$ GeV		Different-flavour leptons

VZ → bb: systematic uncertainties

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

VBF+γ $H \rightarrow bb$

VBF+γ H→bb: strategy

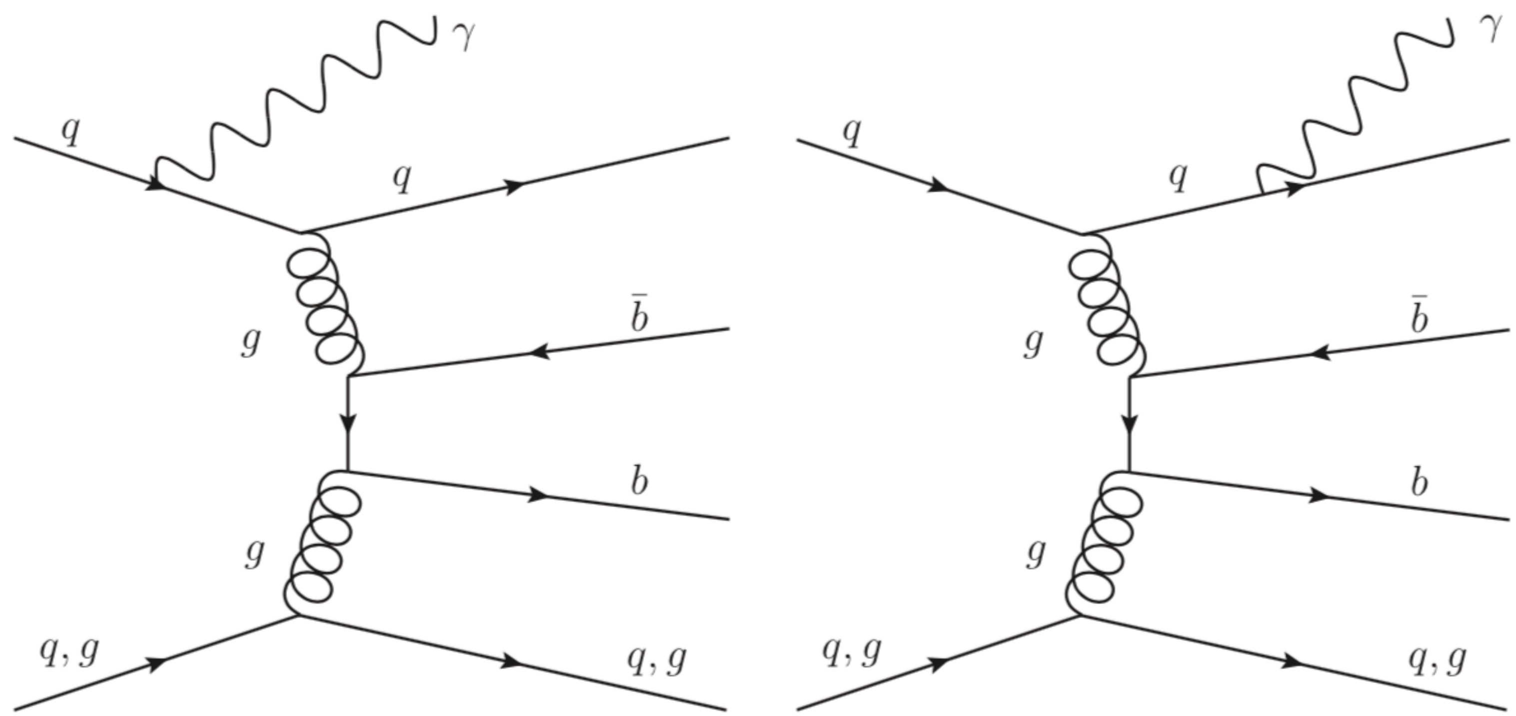
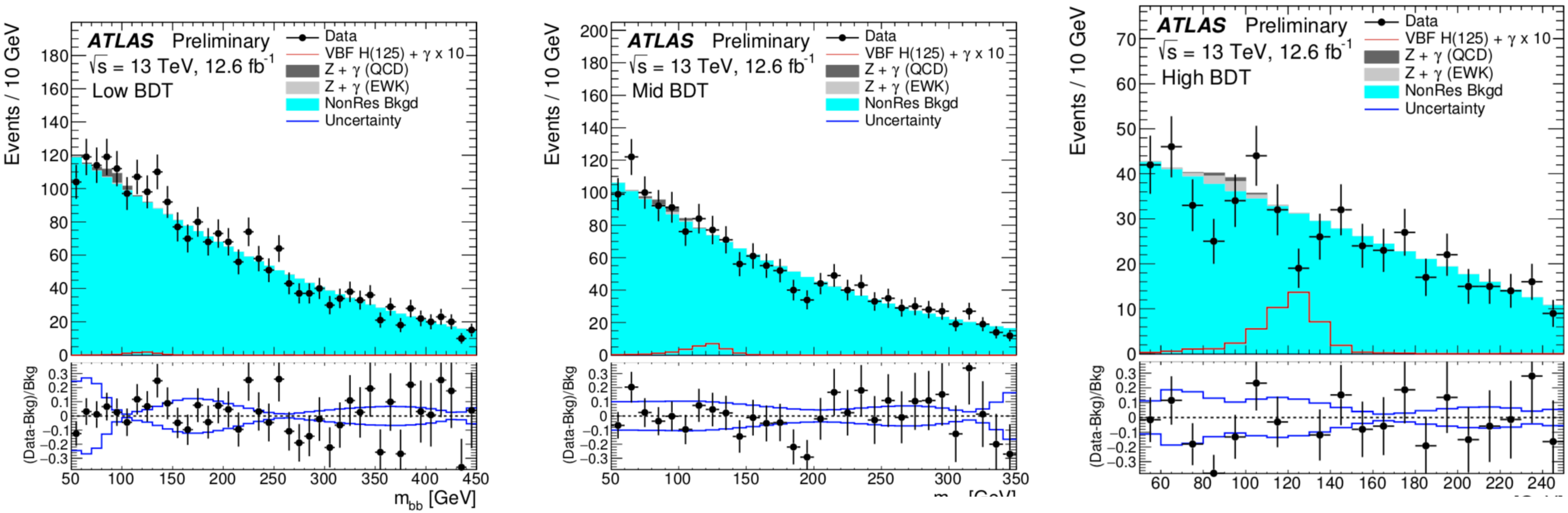


Figure 2: Representative leading-order Feynman diagrams for non-resonant $b\bar{b}$ production in association with a photon and jets.

- Interference between ISR and FSR photons in bkg processes
- Trigger: 1 photon with pT > 25, 4 jets with pT > 35, and mjj > 700 GeV
- BDT separating signal from bkg with minimal correlation to m_{bb}
- Dominant non-resonant bkg fitted in sideband regions (mbb<80 and mbb > 140)

VBF+γ H→bb: results



Result	$H(\to b\bar{b}) + \gamma jj$	$Z(\to b\bar{b}) + \gamma jj$
Expected significance	0.4	1.3
Expected p-value	0.4	0.1
Observed p-value	0.9	0.4
Expected limit	$6.0^{+2.3}_{-1.7}$	$1.8^{+0.7}_{-0.5}$
Observed limit	4.0	2.0
Observed signal strength μ	$-3.9^{+2.8}_{-2.7}$	0.3 ± 0.8

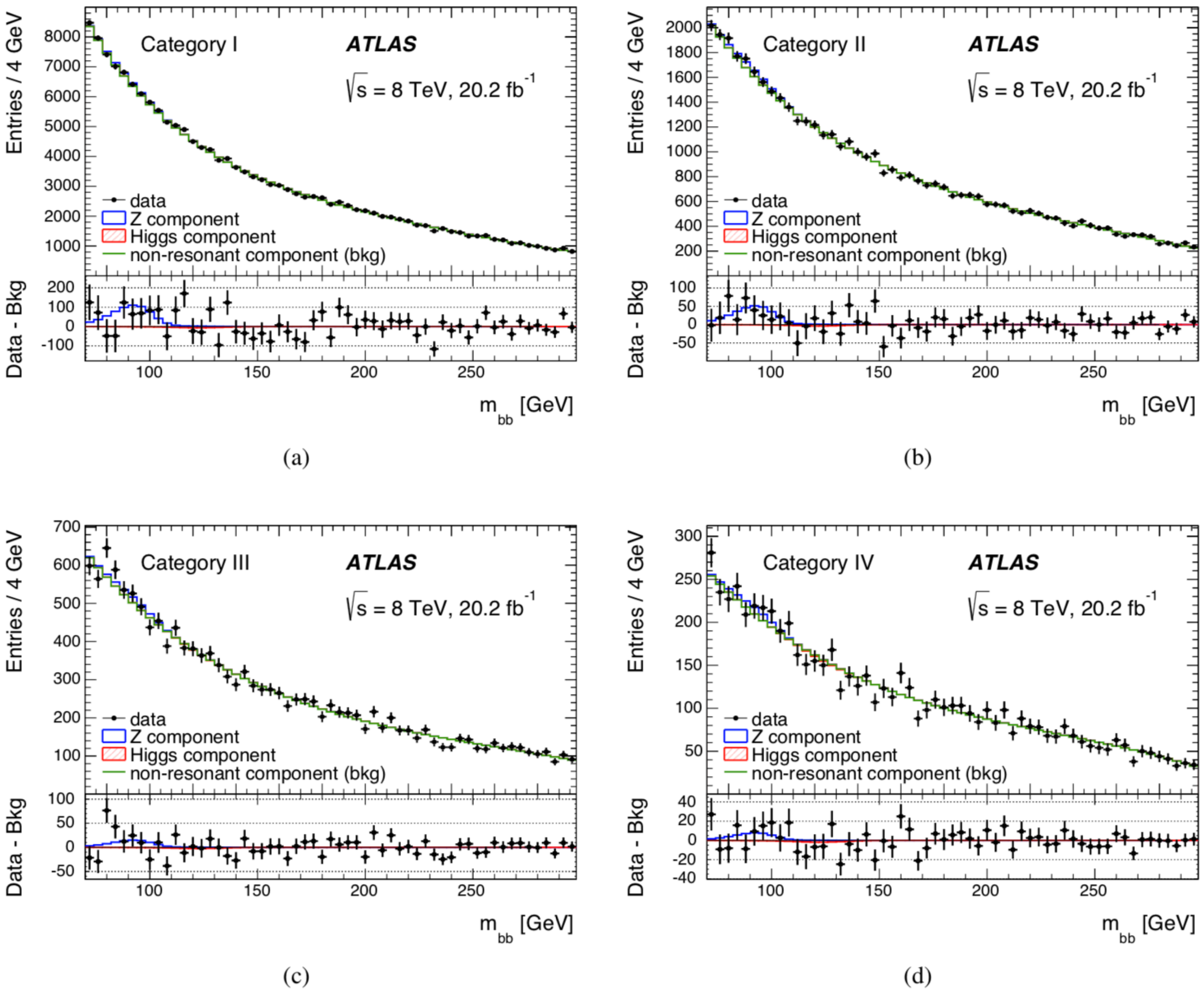
Uncertainty source	Uncertainty $\Delta\mu$
Non-resonant background uncertainty in medium-BDT region	0.22
Non-resonant background uncertainty in high-BDT region	0.21
Non-resonant background uncertainty in low-BDT region	0.17
Parton shower uncertainty on $H + \gamma$ acceptance	0.16
QCD scale uncertainty on $H + \gamma$ cross section	0.13
Jet energy uncertainty from calibration across η	0.10
Jet energy uncertainty from flavour composition in calibration	0.09
Integrated luminosity uncertainty	0.08

VBF $H \rightarrow bb$

VBF $H \rightarrow bb$: strategy

- 4 jets trigger (2 HLT b-tagged)
- BDT trained to separate signal from non resonant background (taken from m_{bb} sidebands)
- BDT used to define 4 categories
- Signal extracted with a fit of m_{bb}

VBF H→bb: results



Source of uncertainty		Uncertainty on μ MVA	Uncertainty on μ Cut-based
Experimental uncertainties	Detector-related	+0.2/−0.3	+1.6/−1.2
	MC statistics	±0.4	±0.1
Theoretical uncertainties	MC signal modelling	±0.1	±1.3
	Z yield	+0.6/−0.5	±1.4
Non-resonant background modelling	Choice of function	±1.0	±1.0
	Sideband statistics	±1.7	±3.7
Statistical uncertainties		±1.3	
Total		±2.3	+4.6/−4.4

μ = -0.8 +/- 2.3

VH→ττ: event selection

Table 3: Summary of the selection criteria for each of the four analysis channels.

Channel	Selections
$W \to \mu\nu/e\nu,\ \ H \to \tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	Exactly one isolated electron and one isolated muon
	Exactly one τ_{had} passing medium BDT ID
	$p_{\mathrm{T}}(\tau_{\mathrm{had}}) > 25$ GeV
	Same-charge e and μ, oppositely charged τ_{had}
	Events containing b-tagged jets with $p_{\mathrm{T}} > 30$ GeV are vetoed
	$\lvert p_{\mathrm{T}}(\tau_{\mathrm{had}})\rvert + \lvert p_{\mathrm{T}}(\mu)\rvert + \lvert p_{\mathrm{T}}(e)\rvert > 80$ GeV
	$\Delta R(\tau_{\mathrm{had}}, \tau_{\mathrm{lep}}) < 3.2$
$W \to \mu\nu/e\nu,\ \ H \to \tau_{\mathrm{had}}\tau_{\mathrm{had}}$	Exactly one isolated electron or one isolated muon
	Exactly two τ_{had} passing medium BDT ID of opposite charge
	$p_{\mathrm{T}}(\tau_{\mathrm{had}}) > 20$ GeV
	$\lvert p_{\mathrm{T}}(\tau^1_{\mathrm{had}})\rvert + \lvert p_{\mathrm{T}}(\tau^2_{\mathrm{had}})\rvert > 100$ GeV
	$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) > 20$ GeV
	$0.8 < \Delta R(\tau^1_{\mathrm{had}}, \tau^2_{\mathrm{had}}) < 2.8$
	Events containing b-tagged jets with $p_{\mathrm{T}} > 30$ GeV are vetoed
$Z \to \mu\mu/ee,\ \ H \to \tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	Exactly three electrons or muons,
	One opposite-charge and same-flavor lepton pair
	with invariant mass $80 < m_{\ell\ell} < 100$ GeV
	Exactly one τ_{had} passing medium BDT ID, with opposite charge
	to the lepton assigned to the Higgs boson
	$p_{\mathrm{T}}(\tau_{\mathrm{had}}) > 20$ GeV
	$\lvert p_{\mathrm{T}}(\tau_{\mathrm{had}})\rvert + \lvert p_{\mathrm{T}}(\tau_{\mathrm{lep}})\rvert > 60$ GeV
$Z \to \mu\mu/ee,\ \ H \to \tau_{\mathrm{had}}\tau_{\mathrm{had}}$	Exactly two electrons or two muons of opposite charge
	Exactly two τ_{had} passing medium BDT ID of opposite charge
	$p_{\mathrm{T}}(\tau_{\mathrm{had}}) > 20$ GeV
	$60 < m_{\ell\ell} < 120$ GeV
	$\lvert p_{\mathrm{T}}(\tau^1_{\mathrm{had}})\rvert + \lvert p_{\mathrm{T}}(\tau^2_{\mathrm{had}})\rvert > 88$ GeV

VH→ττ: signal regions

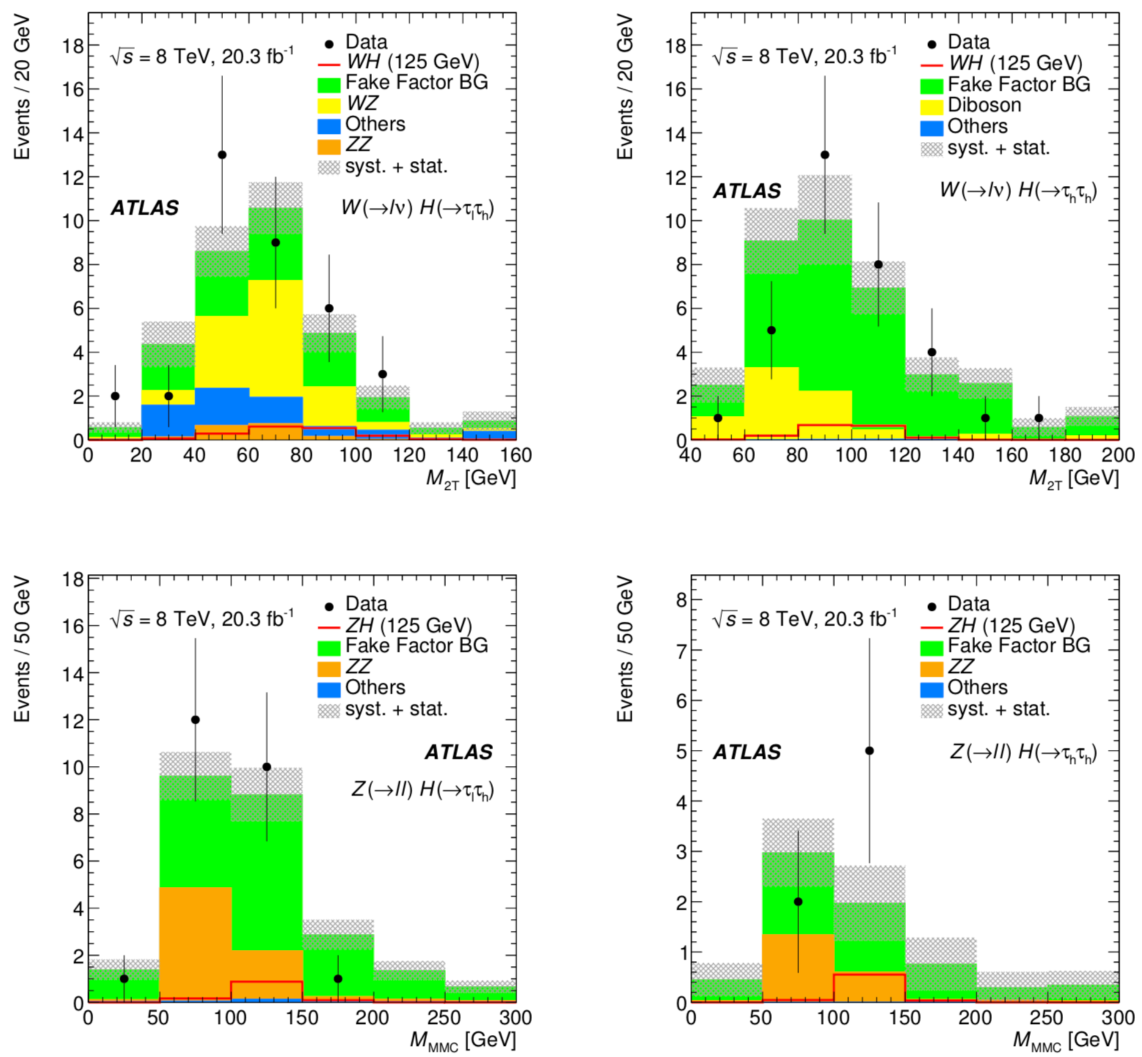


Figure 2: Mass distributions used to determine the strength of signal in each channel. Upper left: M_{2T} distribution for the $WH \to \tau_{\text{lep}}\tau_{\text{had}}$ channel. Upper right: M_{2T} distribution for the $WH \to \tau_{\text{had}}\tau_{\text{had}}$ channel. Lower left: M_{MMC} distribution for the $ZH \to \tau_{\text{lep}}\tau_{\text{had}}$ channel. Lower right: M_{MMC} distribution for the $ZH \to \tau_{\text{had}}\tau_{\text{had}}$ channel.

WH channels:
Dominated by Fakes in hadhad
Fakes + WZ in lephad

ZH channels:
Dominated by Fakes in hadhad
Some ZZ contribution

Channel	Obs.	Signal	Σ Background	Fake Factor	Diboson	Other
$W \to \mu\nu/e\nu,\ \ H \to \tau_{\text{lep}}\tau_{\text{had}}$	35	1.95 ± 0.05	32.4 ± 1.9	13.1 ± 1.3	13.54 ± 0.35	5.7 ± 1.4
$W \to \mu\nu/e\nu,\ \ H \to \tau_{\text{had}}\tau_{\text{had}}$	33	1.84 ± 0.04	35.5 ± 2.7	28.1 ± 2.4	7.4 ± 1.2	-
$Z \to \mu\mu/ee,\ \ H \to \tau_{\text{lep}}\tau_{\text{had}}$	24	1.14 ± 0.03	24.6 ± 1.5	17.1 ± 1.5	7.28 ± 0.16	0.20 ± 0.01
$Z \to \mu\mu/ee,\ \ H \to \tau_{\text{had}}\tau_{\text{had}}$	7	0.64 ± 0.02	6.8 ± 1.2	4.7 ± 1.2	2.09 ± 0.09	0.012 ± 0.003

VH→ττ: results

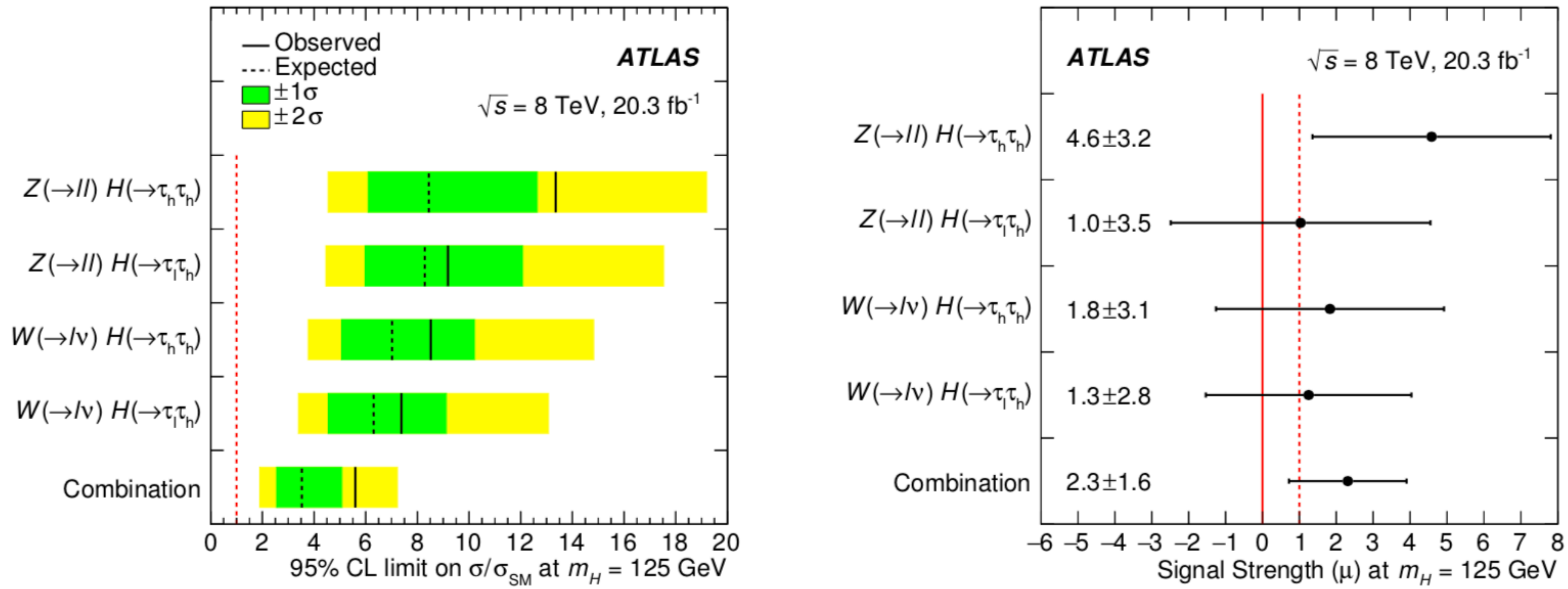


Figure 3: The combined result for the VH channels. The 95% CL cross section limit is shown for each individual channel on the left. The right figure shows the signal strength in each individual channel, along with the combination.

Table 7: The expected and observed significances for the four channels.

Channel	Expected significance	Observed significance
$W \to \mu\nu/e\nu,\quad H \to \tau_{\text{lep}}\tau_{\text{had}}$	$0.36\ \sigma$	$0.44\ \sigma$
$W \to \mu\nu/e\nu,\quad H \to \tau_{\text{had}}\tau_{\text{had}}$	$0.32\ \sigma$	$0.60\ \sigma$
$Z \to \mu\mu/ee,\quad H \to \tau_{\text{lep}}\tau_{\text{had}}$	$0.28\ \sigma$	$0.29\ \sigma$
$Z \to \mu\mu/ee,\quad H \to \tau_{\text{had}}\tau_{\text{had}}$	$0.32\ \sigma$	$1.38\ \sigma$

VBF CP analysis: $H \rightarrow \tau\tau$

VBF CP analysis: Optimal Observable

D. Atwood et al.: PRD45 (1992) 2405–2413
M. Davier et al.: PLB306 (1993) 411–417
M Diehl et al.: Z. Phys. C62 (1994) 397–412

VBF CP analysis: BDT Control regions

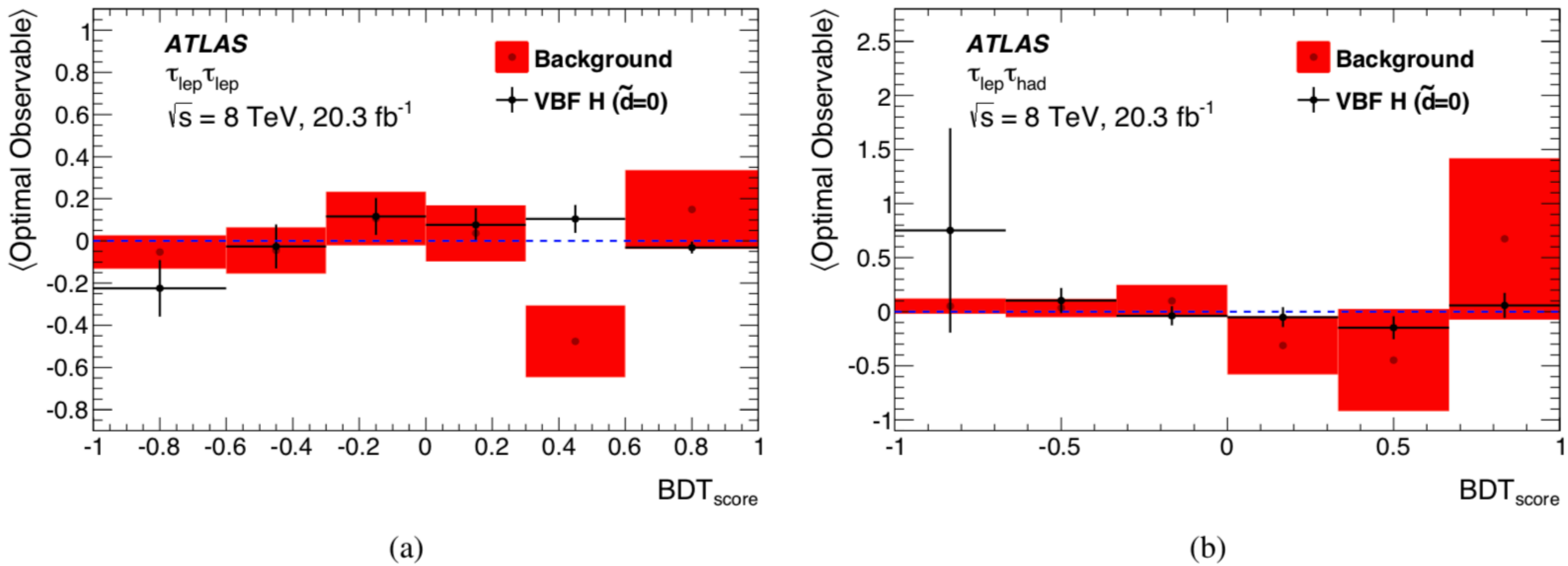


Figure 2: Mean of the *Optimal Observable* as a function of the BDT$_{score}$ for the SM signal (black dots with error bars) and for the sum of all background processes (filled red area), for the (a) $\tau_{lep}\tau_{lep}$ and (b) $\tau_{lep}\tau_{had}$ channel. The signal and background model is in agreement with the hypothesis of no bias from the BDT score.