Measurements and searches of Higgs boson decays to two fermions

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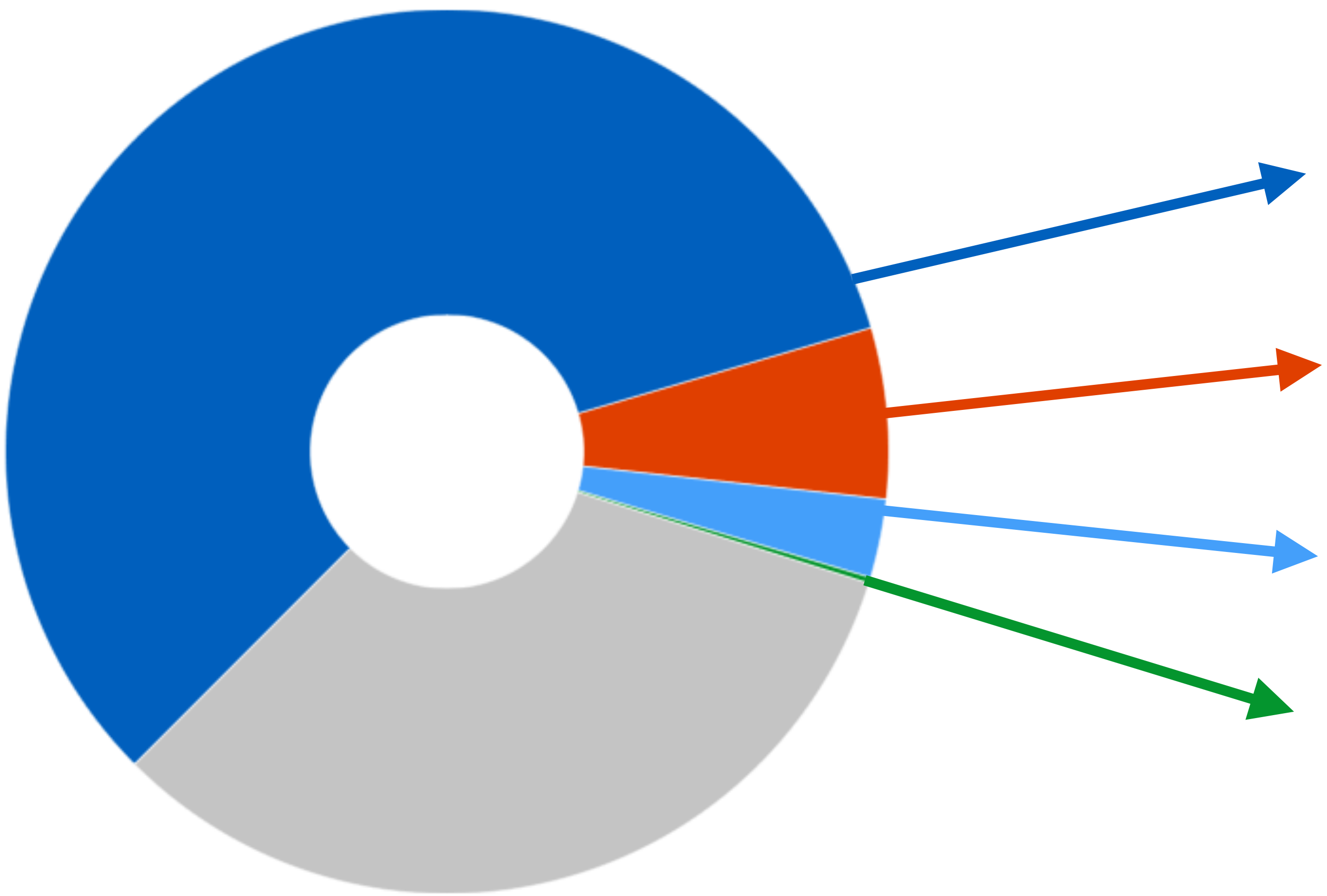
for the ATLAS Collaboration

What We Talk About

when we talk about
Higgs to fermions

Higgs **decays to pairs of fermions** allow to test Standard Model Yukawa couplings and are characterised by **very different branching ratios**, ranging over four orders of magnitude!



$$\mathbf{H} \rightarrow \mathbf{b\bar{b}} \qquad (\sim \mathbf{58}\%)$$

$$\mathbf{H} \rightarrow \tau^+\tau^- \qquad (\sim \mathbf{6.3}\%)$$

$$\mathbf{H} \rightarrow \mathbf{c\bar{c}} \qquad (\sim \mathbf{2.9}\%)$$

$$\mathbf{H} \rightarrow \mu^+\mu^- \qquad (\sim \mathbf{0.022}\%)$$

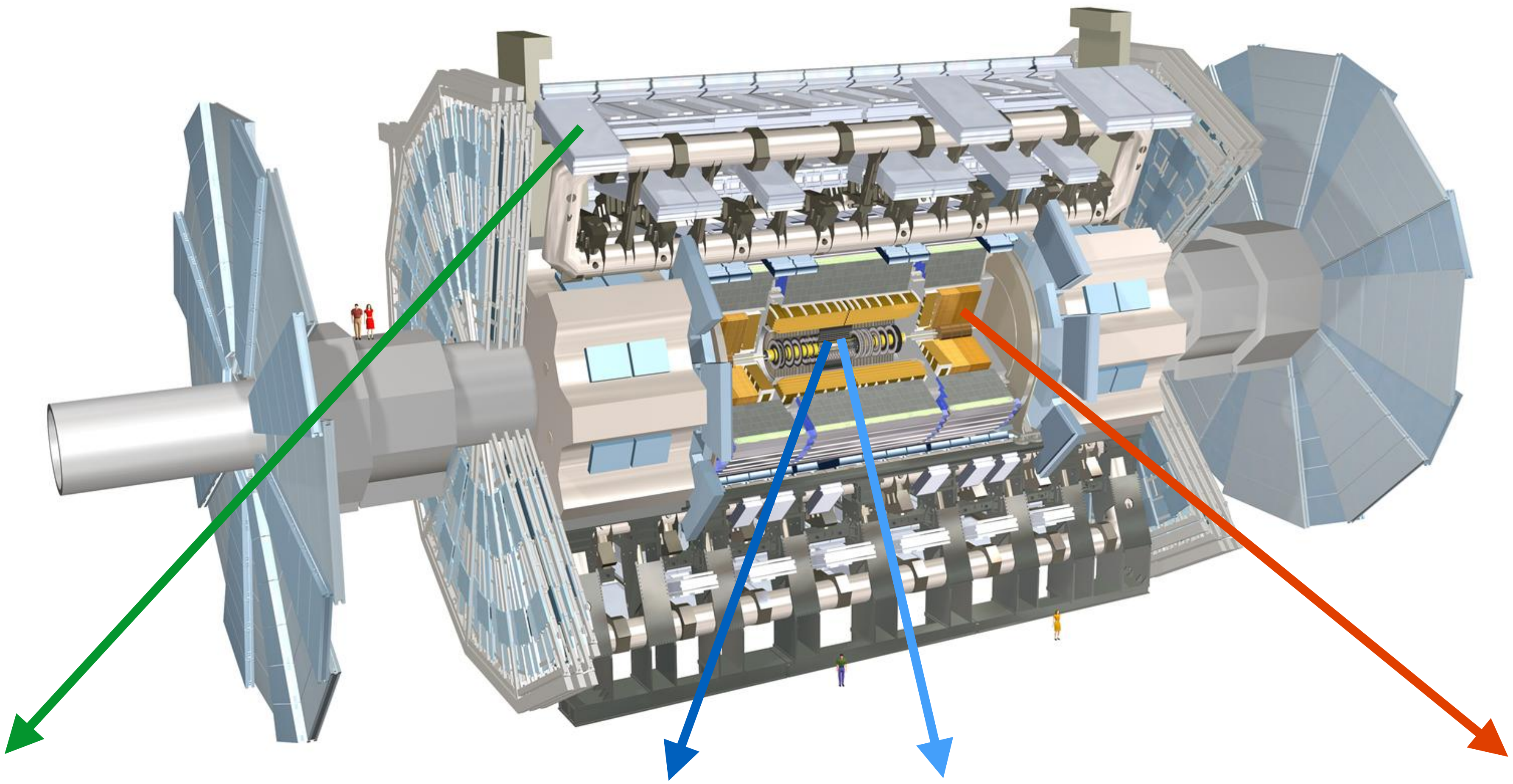
Each decay mode also corresponds to **very different experimental challenges**, e.g.:

- **beauty pairs** are submerged in **direct beauty quark pair production**
- **tau pairs** require very good **hadronic decay identification and leptonic decay reconstruction**
- **muon pairs** have a clean signature, but are **very rare**
- **charm pairs** suffer from backgrounds as for beauty, but are **more difficult to identify**

What We Talk About

when we talk about Higgs to fermions

Searches for these decays require to **push to the limit the performance of all detectors and of combined reconstruction in different areas**



$\mathbf{H} \to \mu^+\mu^-$

Requires **triggering and tracking with the Muon Spectrometer**, inner tracking and isolation information

$\mathbf{H} \to \mathbf{b\bar{b}}$ $\mathbf{H} \to \mathbf{c\bar{c}}$

Based on **track and vertex reconstruction** in the **Inner Detector**, to perform jet **b/c flavour tagging** even in very dense environments

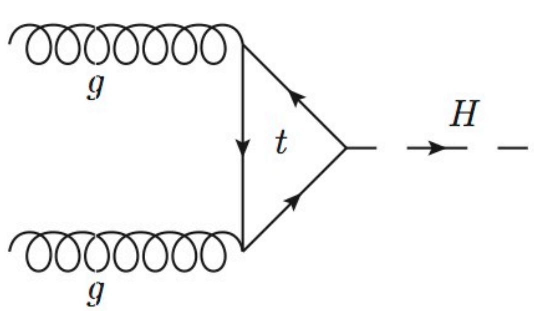
$\mathbf{H} \to \tau^+\tau^-$

Uses both **Inner Detector and Calorimeters**, to identify hadronic tau decays and reconstruct leptonic decays (e.g. electron identification)

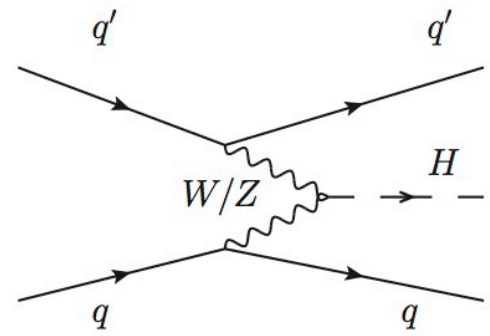
What We Talk About

when we talk about
Higgs to fermions

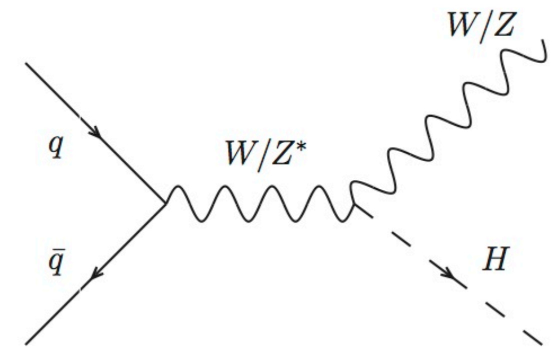
Yet **another difference** between Higgs measurements is the **production channel** under study



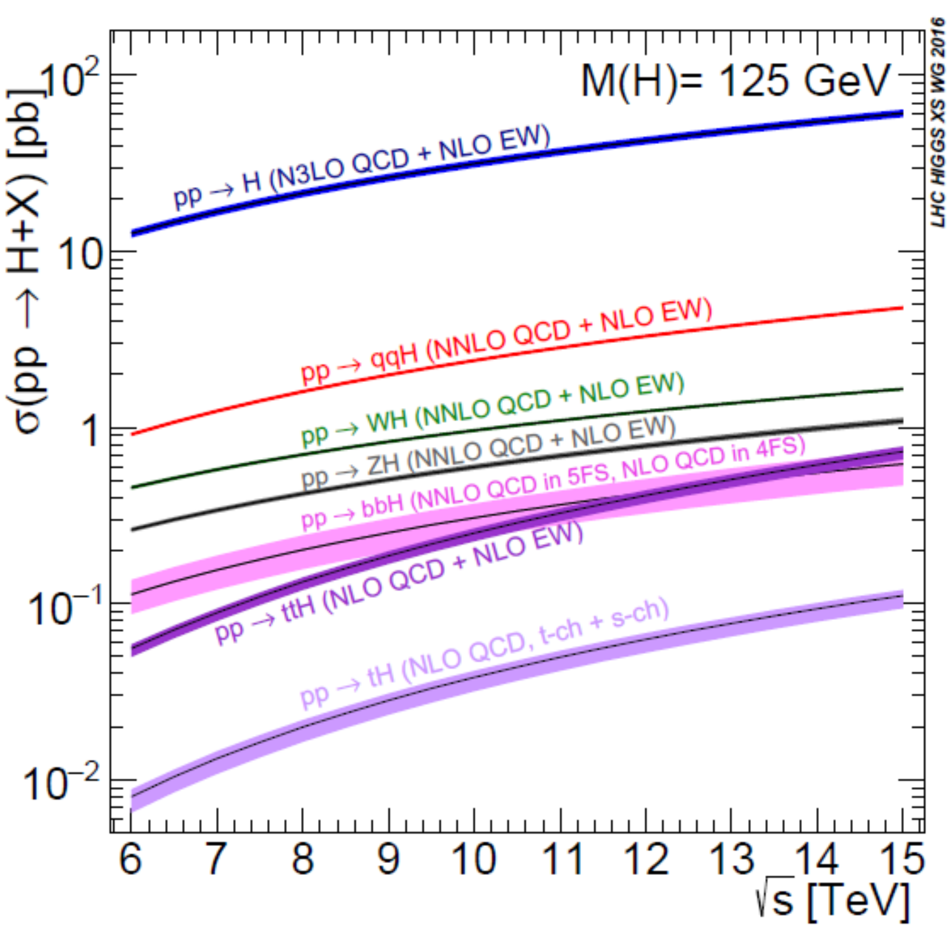
Gluon fusion (ggF)
Largest production rate, but **no distinctive feature**



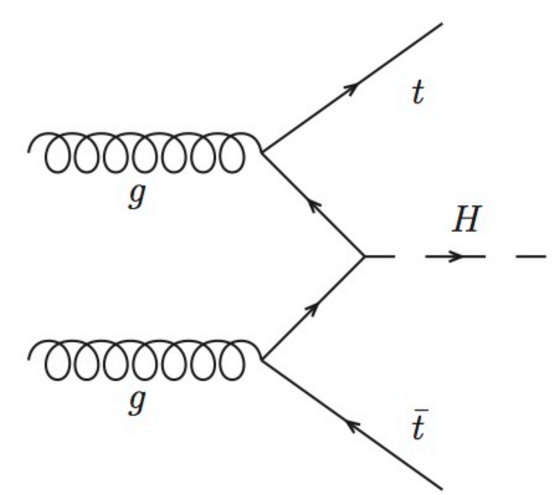
Vector-Boson fusion (VBF)
Distinct topology, two VBF jets and low central activity, allows **effective selection**



Associated Vector Boson production (VH)
Leptonic decays of the associated Vector Boson **help triggering and selecting** candidate events



Associated top pair production
As the Higgs boson cannot decay to a top quark pair, this channel provides a **unique test of Higgs coupling to top quarks**
Covered by Arthur Chomont (yesterday's morning session)



Summary

ATLAS produced many results since Higgs boson discovery, in different production modes

LEPTONIC FINAL STATES		
H→mumu PRL 119 (2017) 051802	13 TeV	36 fb^{-1}
H→tautau JHEP 04 (2015) 117	7,8 TeV	25 fb^{-1}
VH, H→tautau PRD 93, 092005 (2016)	8 TeV	20 fb^{-1}
VBF H, H→tautau Eur. Phys. J. C76 (2016) 658	8 TeV	20 fb^{-1}

QUARK FINAL STATES		
VH, H→bb JHEP 12 (2017) 024	13 TeV	36 fb^{-1}
VBF H, H→bb JHEP 11 (2016) 112	8 TeV	20 fb^{-1}
VBF H+gamma, H→bb ATLAS-CONF-2016-063	13 TeV	13 fb^{-1}
ZH, H→cc arXiv:1802.04329	13 TeV	36 fb^{-1}

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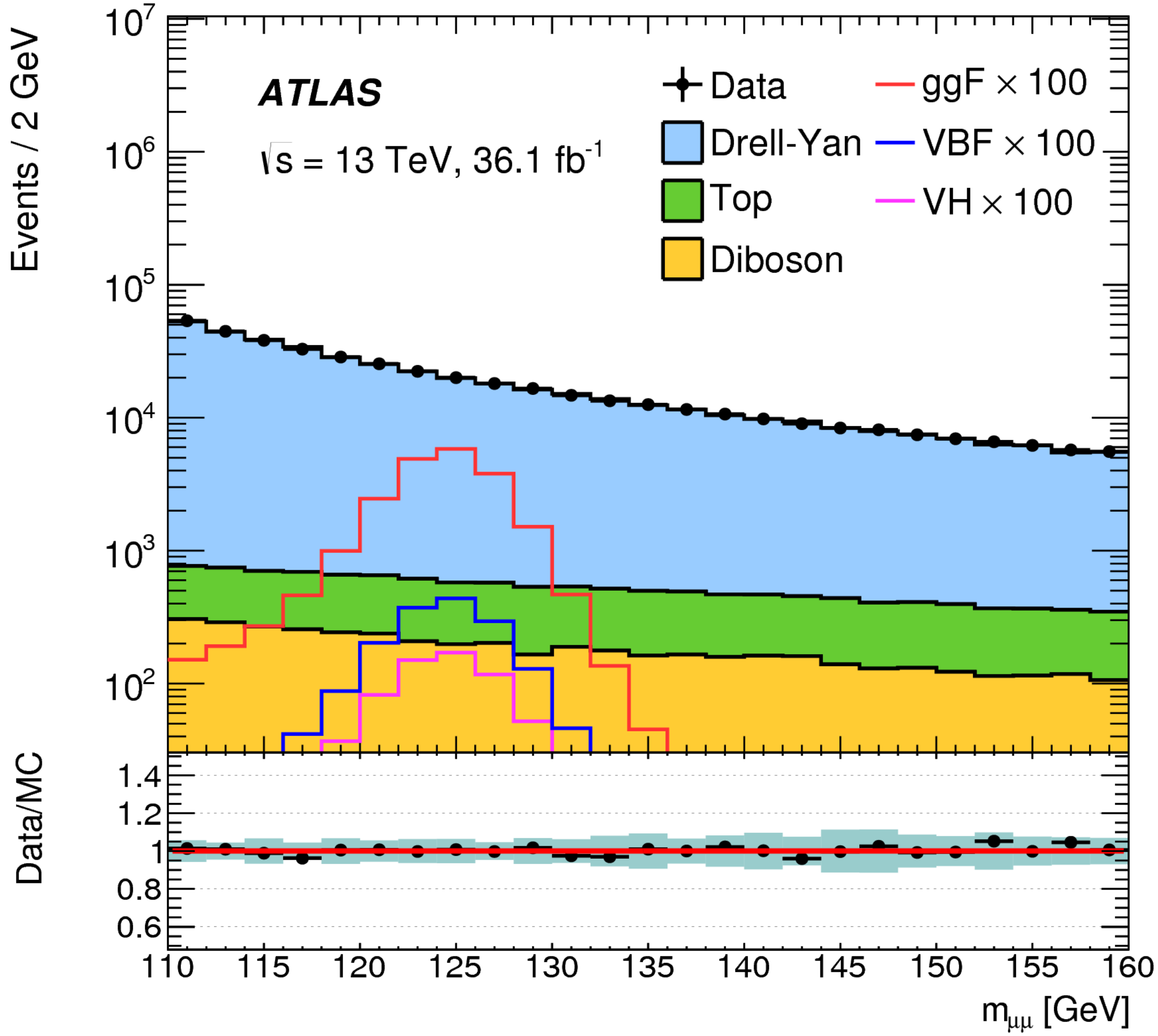
ZH, H→cc arXiv:1802.04329	13 TeV	36 fb^{-1}

This talk will focus on **most recent results** and, additionally, on

H/Z→ϕ/ρ+gamma arXiv:1712.02758	13 TeV	36 fb^{-1}

Search for H→μ⁺μ⁻: analysis outline

This decay channel provides a **very clean signature**, with easy access to efficient triggers
At the same time, signal is diluted in an **overwhelming background (mainly Drell-Yan)**



No assumption is made a priori **on production** and topology

Opposite sign **isolated muons** selected, and invariant mass is required to fall in 110-160 GeV

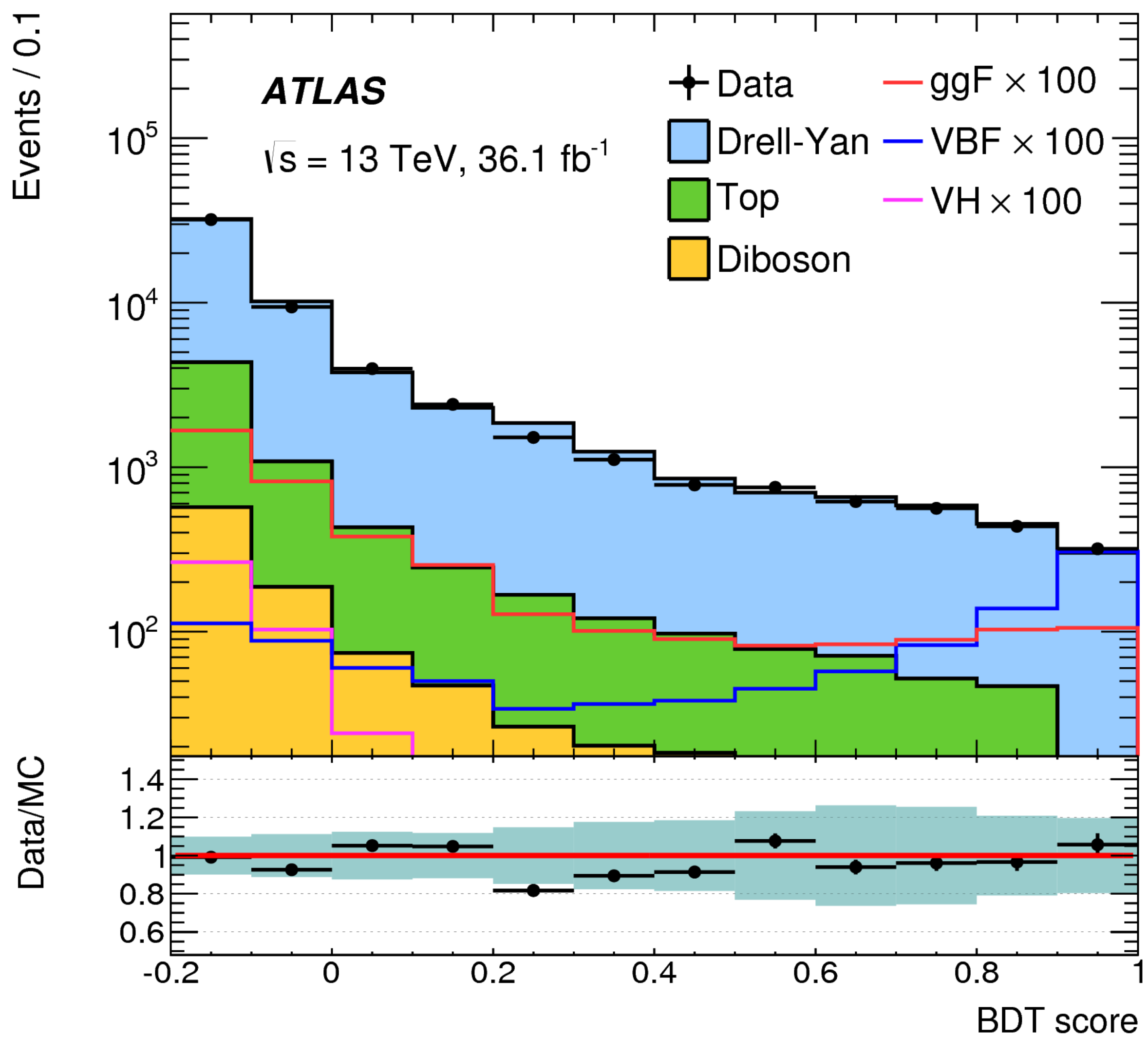
Background modelled with Breit-Wigner convoluted with Gaussian (Z-peak) + exponentially falling continuum

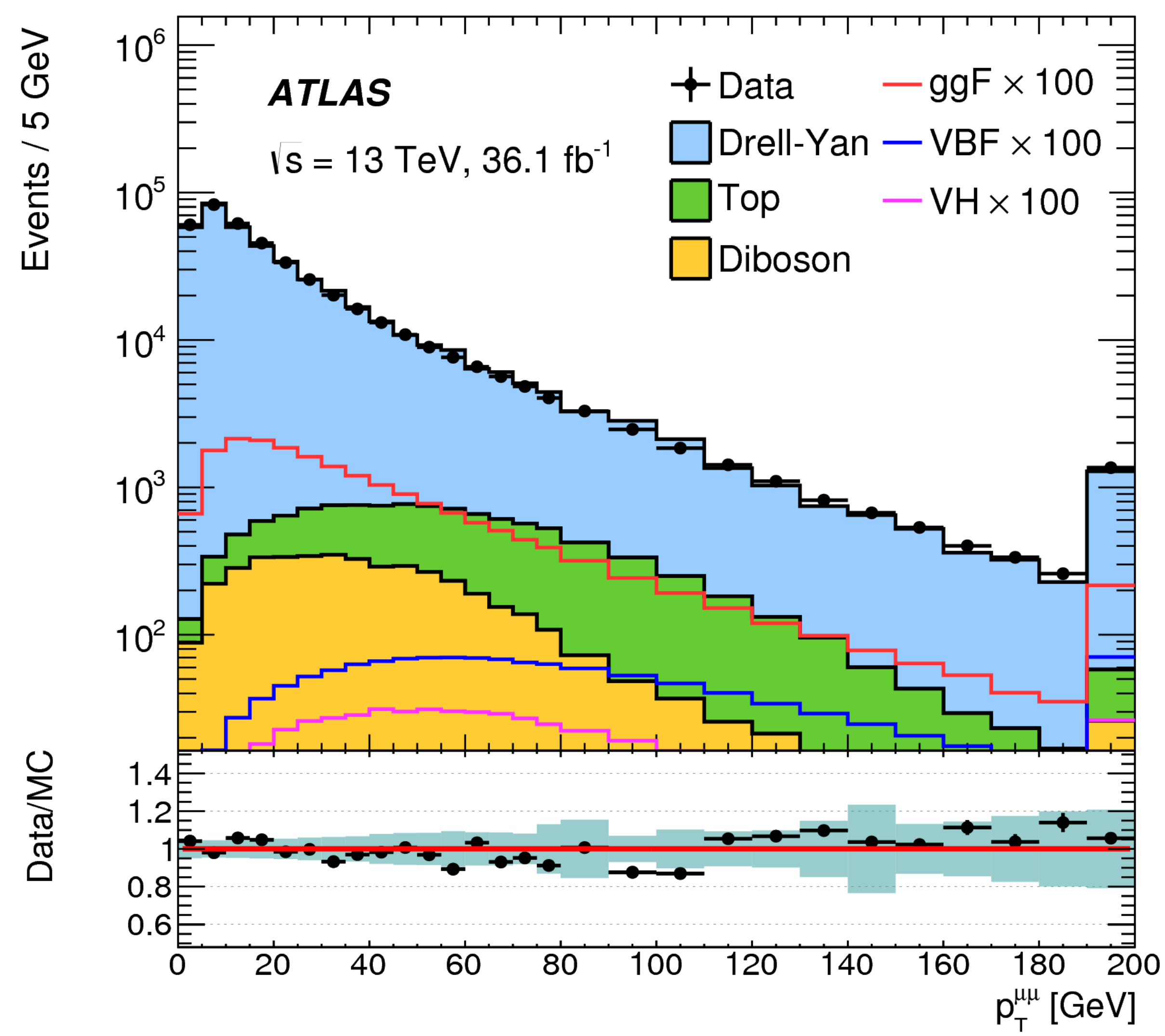
A Boosted Decision Tree (BDT) is trained to separate the VBF contribution from ggF

Eight categories are defined, based on kinematics and BDT

Search for H→μ⁺μ⁻: categories

For events containing **at least two jets**, two **high BDT score** categories are defined
Other events categorised using **dimuon traverse momentum $p_T^{\mu\mu}$ and muon pseudorapidity**





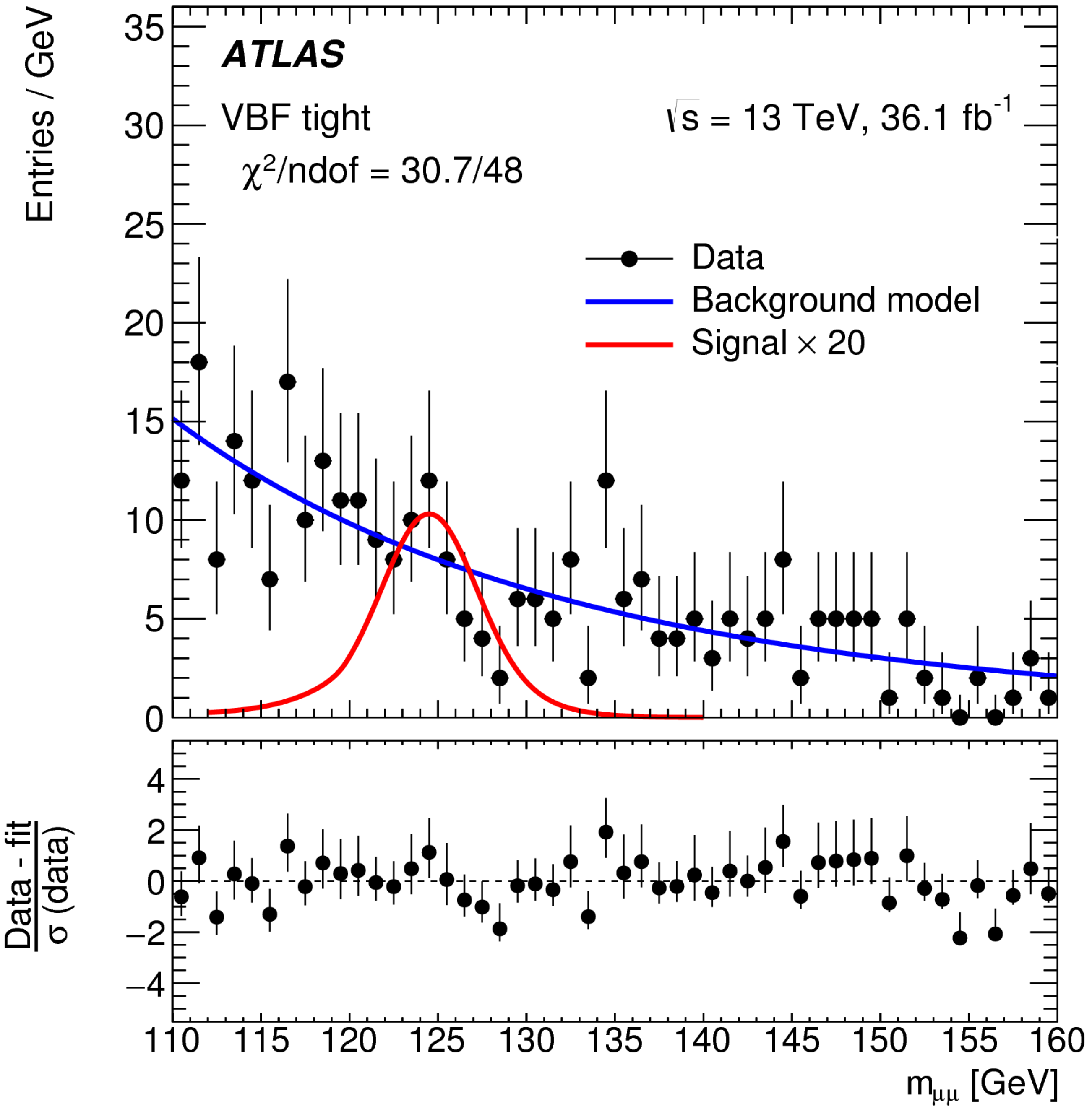
Best signal (S) to bkg (B) found for **highest BDT (VBF)** and **non-central high-pT (ggF)** categories

	S	B	$S/\sqrt{B}$	FWHM	Data
Non-central high $p_T^{\mu\mu}$	40	13000	0.35	7.7 GeV	12829
VBF tight	3.4	78	0.38	7.5 GeV	79

Search for $H \rightarrow \mu^+\mu^-$: results

After combined mass fits, **no significant excess is observed** within the analysed mass range

Signal strength definition: $\mu = \sigma \times BR / \sigma_{SM} \times BR_{SM}$



Mass fit for best category (stat. errors on data)

The analysis is limited by available statistics rather than systematics

95% upper limits

Observed: 3.0 x SM

Expected: 3.1 x SM

Signal strength $\mu = -0.1 \pm 1.5$

95% upper limits combined with Run 1

Observed: 2.8 x SM

Expected: 2.9 x SM

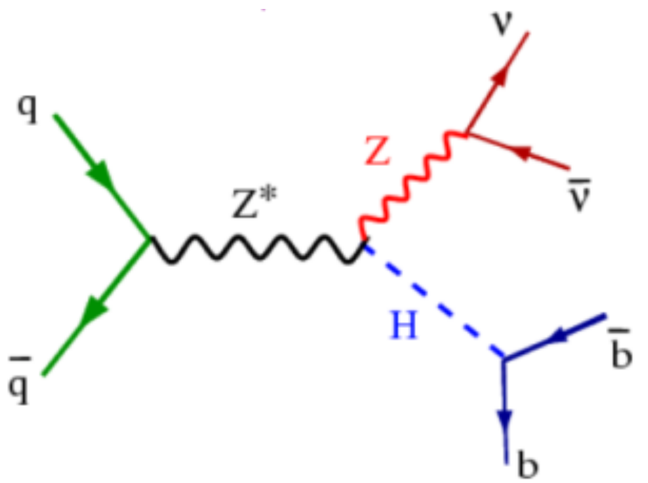
Signal strength $\mu = -0.1 \pm 1.4$

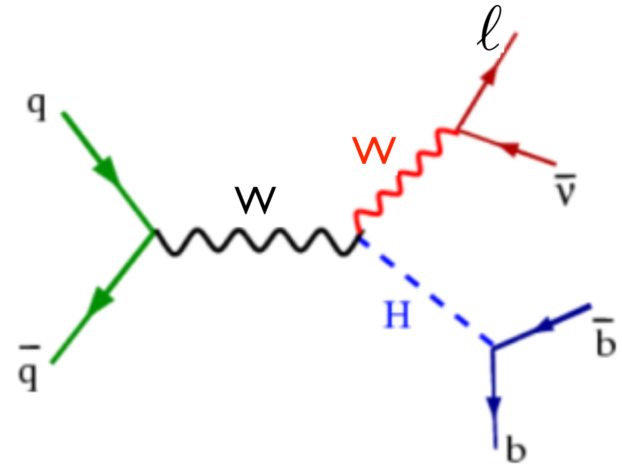
Prospects

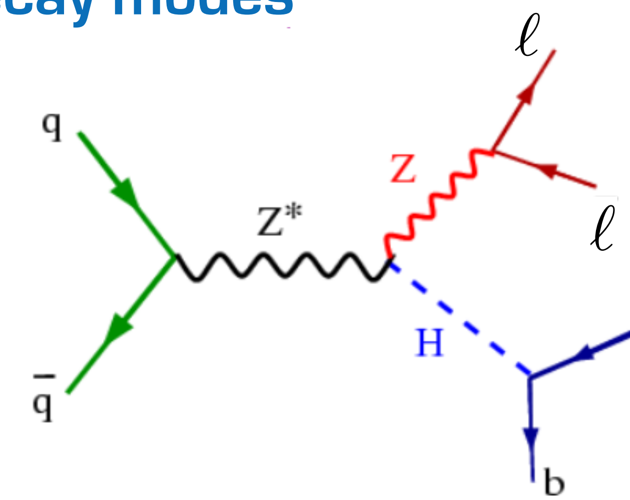
Could reach 1 x SM combining with CMS results by the end of Run 2

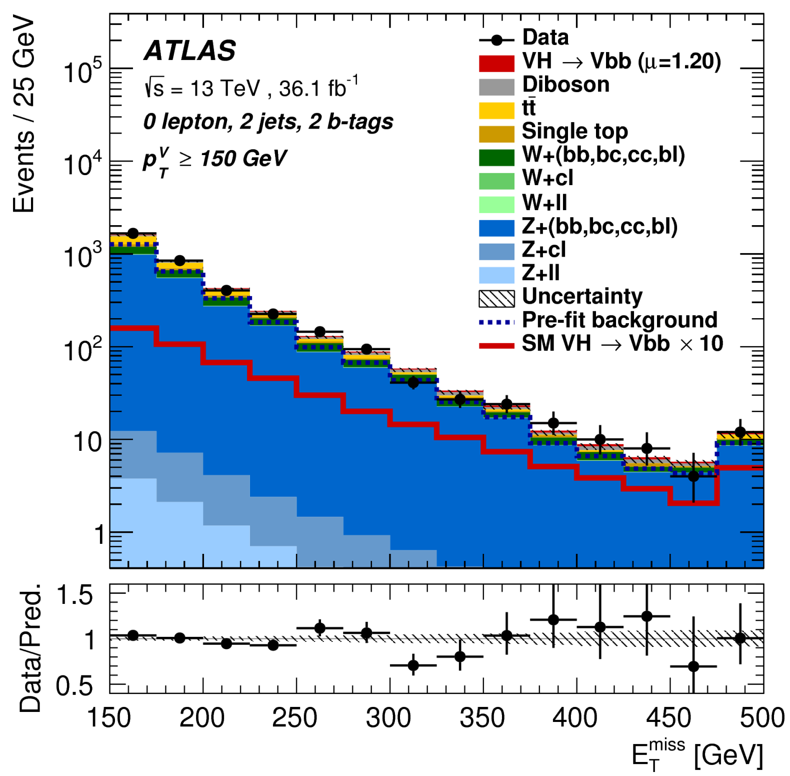
Evidence for VH, H→bb: analysis outline

Associated **VH production** is the **most sensitive probe of Higgs decays to beauty** quark pairs
Subdivided in three analysis channels, depending on **vector boson decay modes**

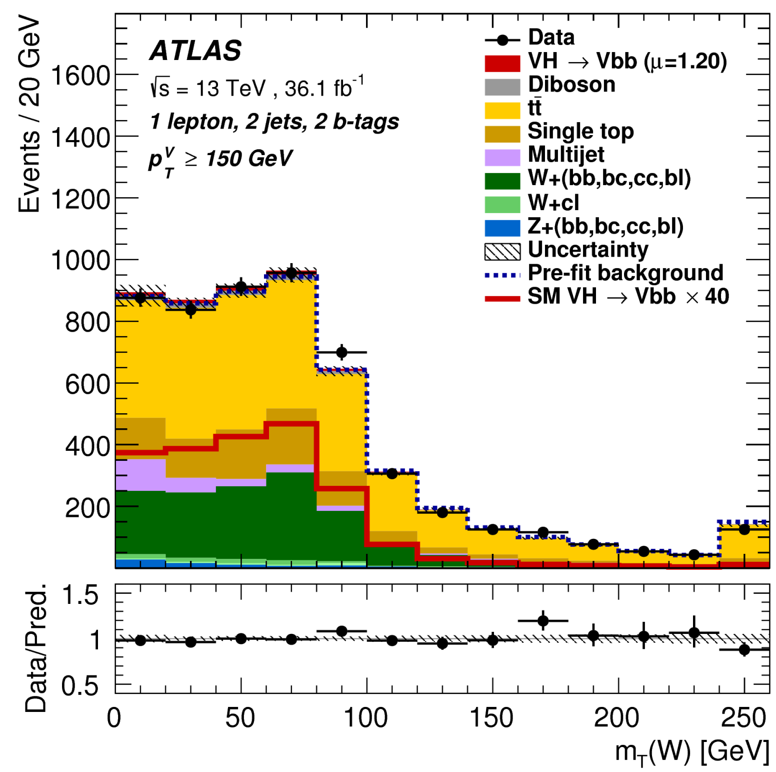




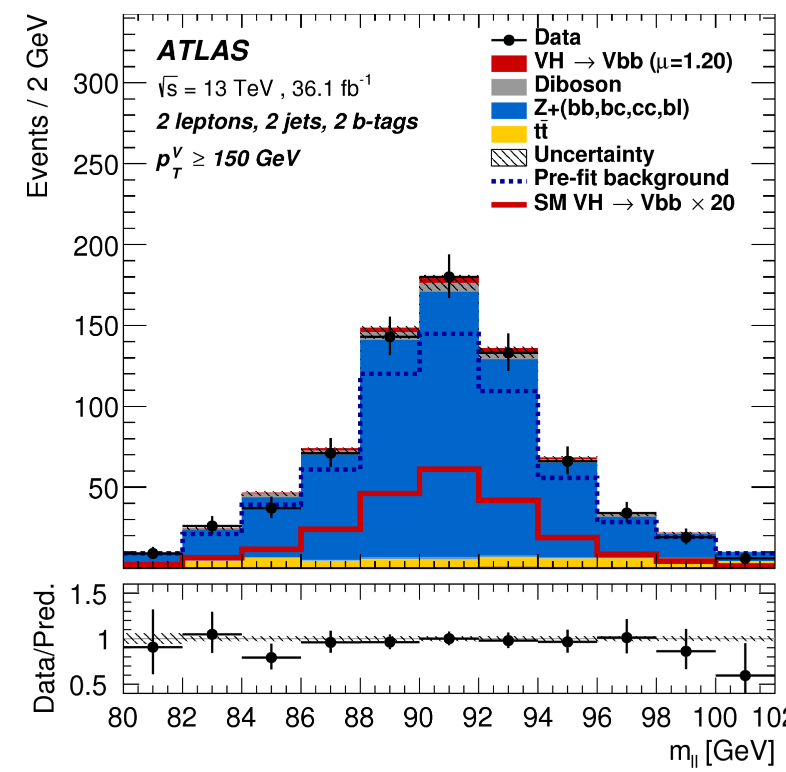




0-lepton final state



1-lepton final state

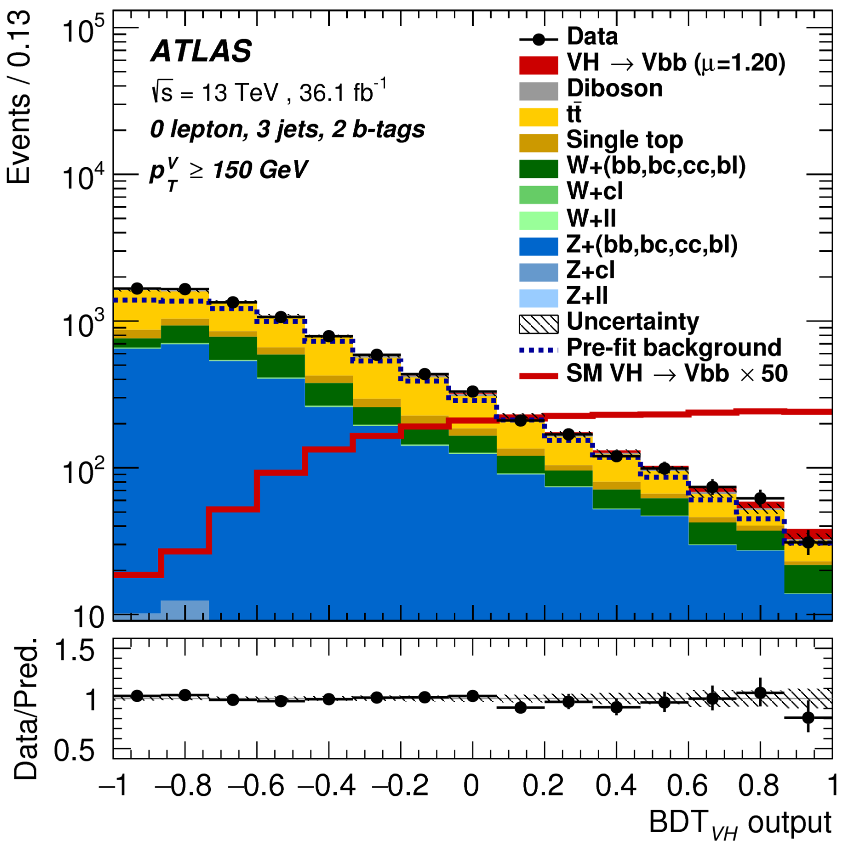


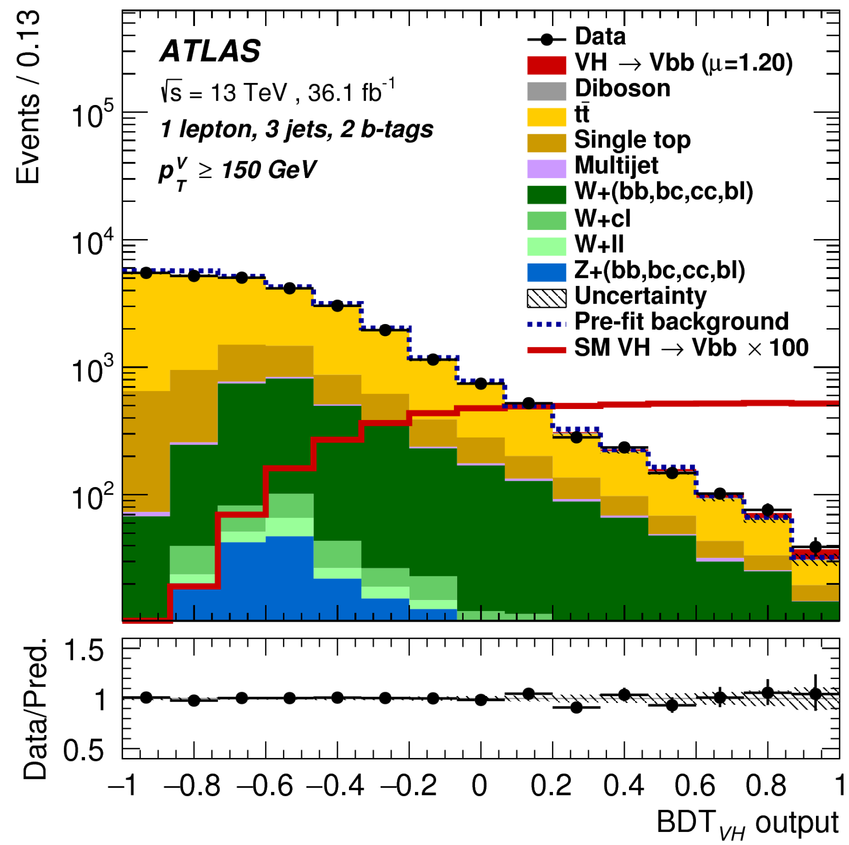
2-lepton final state

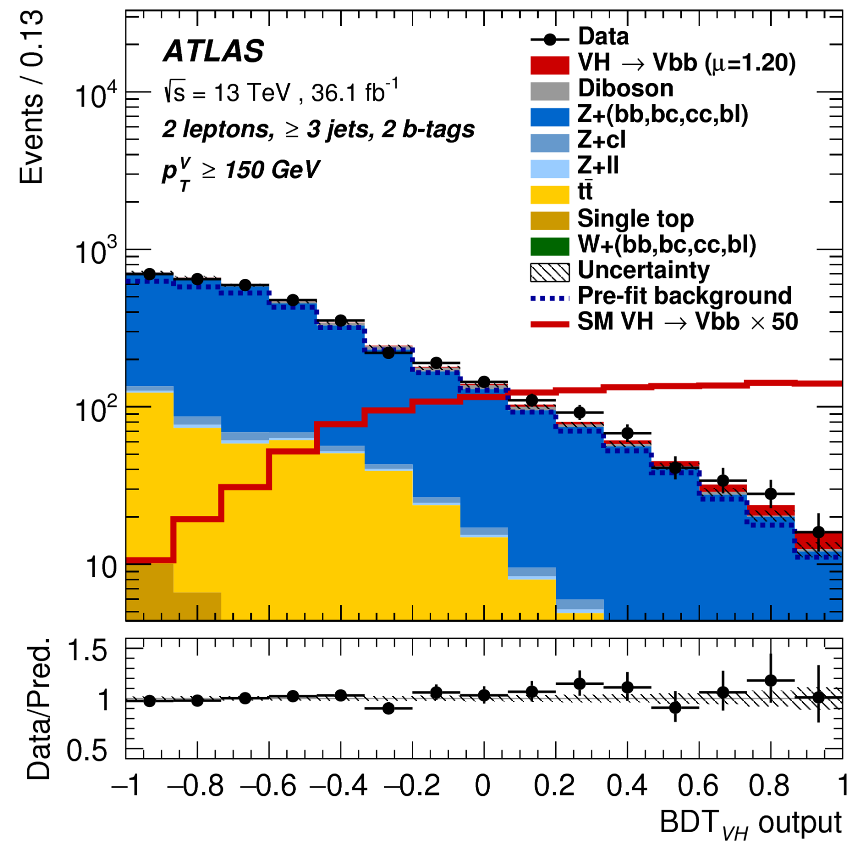
Triggered by missing transverse energy (MET) or single leptons
Main bkg from **Z + Heavy Flavour**, **W + Heavy Flavour**, **top pairs** is taken from simulation
In all cases **2 b-tagged jets required** out of 2/3 jets (0,1-lepton), 2/≥3 jets (2-lepton)

Evidence for VH, H→bb: categories

For each lepton-number, a **BDT is trained using event kinematics, to be used as discriminant**
Based on lepton-number, jet multiplicity and vector boson p_T, **8 signal categories are defined**







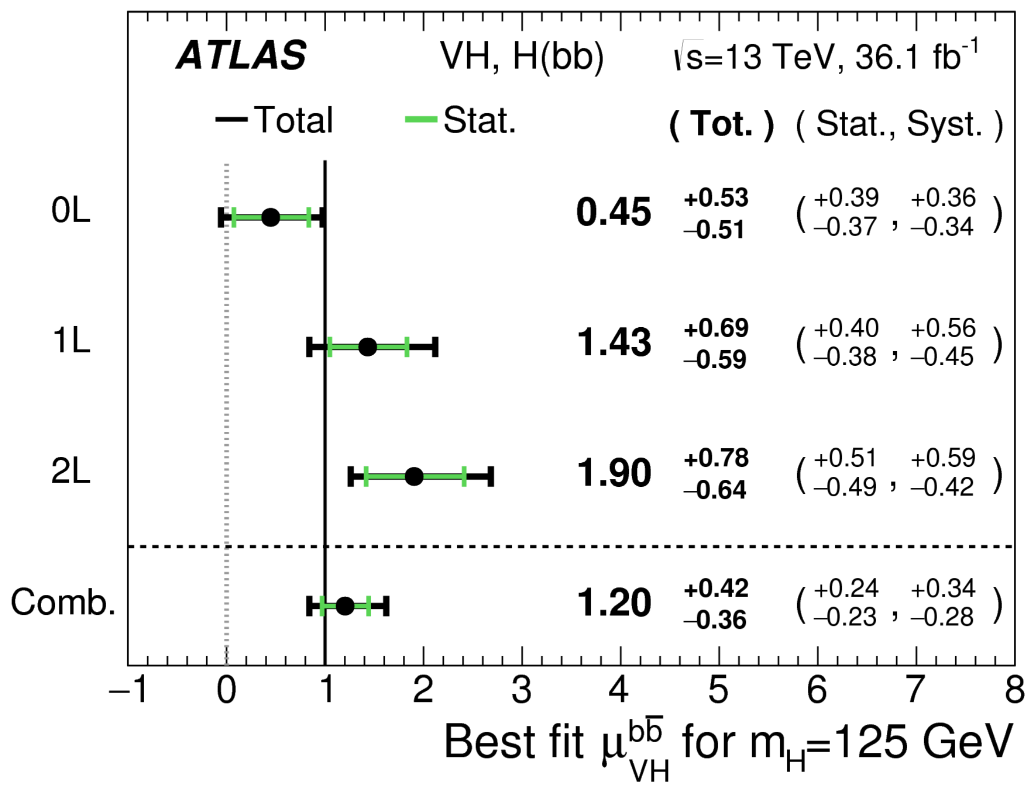
In addition, **6 control regions are defined**, among which:
1-lepton control region used to constrain W+HF background
2-lepton (electron+muon) control region used to constrain top pair background

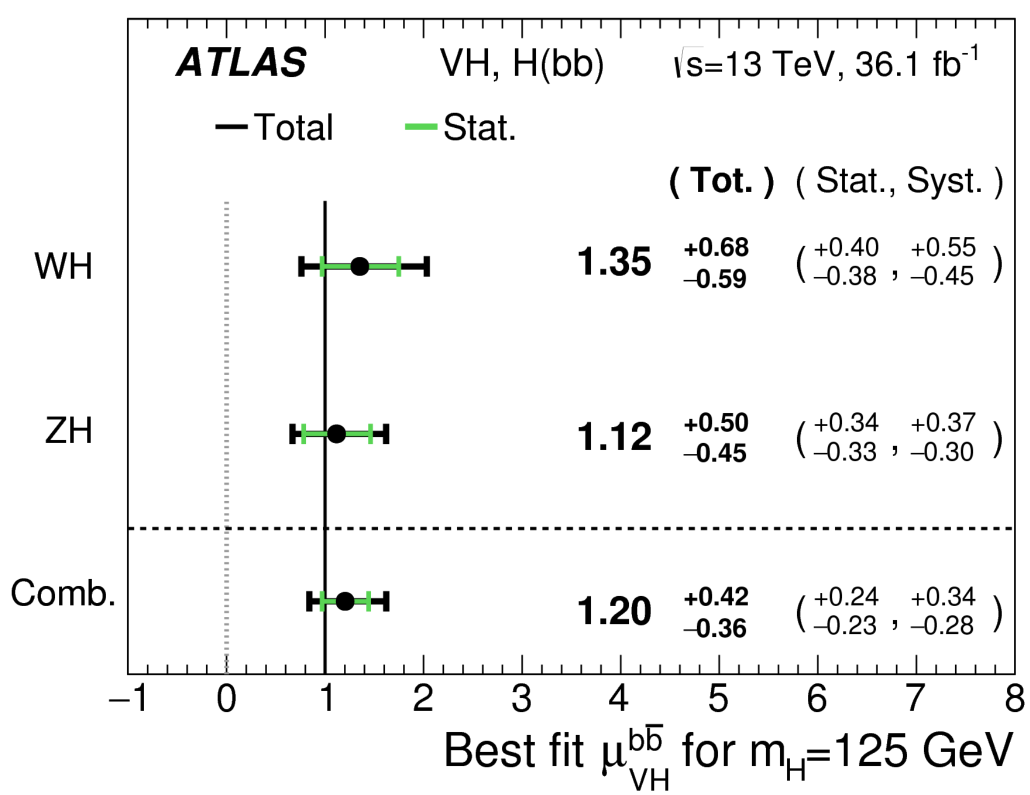
A **simultaneous maximum likelihood fit to signal categories and control regions** is performed

The fit extracts, at the same time, the signal strength and the **normalisations of the largest backgrounds (top pairs and Z/W+HF)**

Evidence for VH, H→bb: results

Fit results are compared **for each lepton-number category and separately for ZH and WH**





Results are found to be **compatible with each other and with SM expectations**

Significance

Observed: 3.5 σ   Expected: 3.0 σ

Significance combined with Run 1

Observed: 3.6 σ   Expected: 4.0 σ

Evidence for H→bb decays!

Uncertainty is dominated by systematics

Leading contributions (in terms of σ_μ)

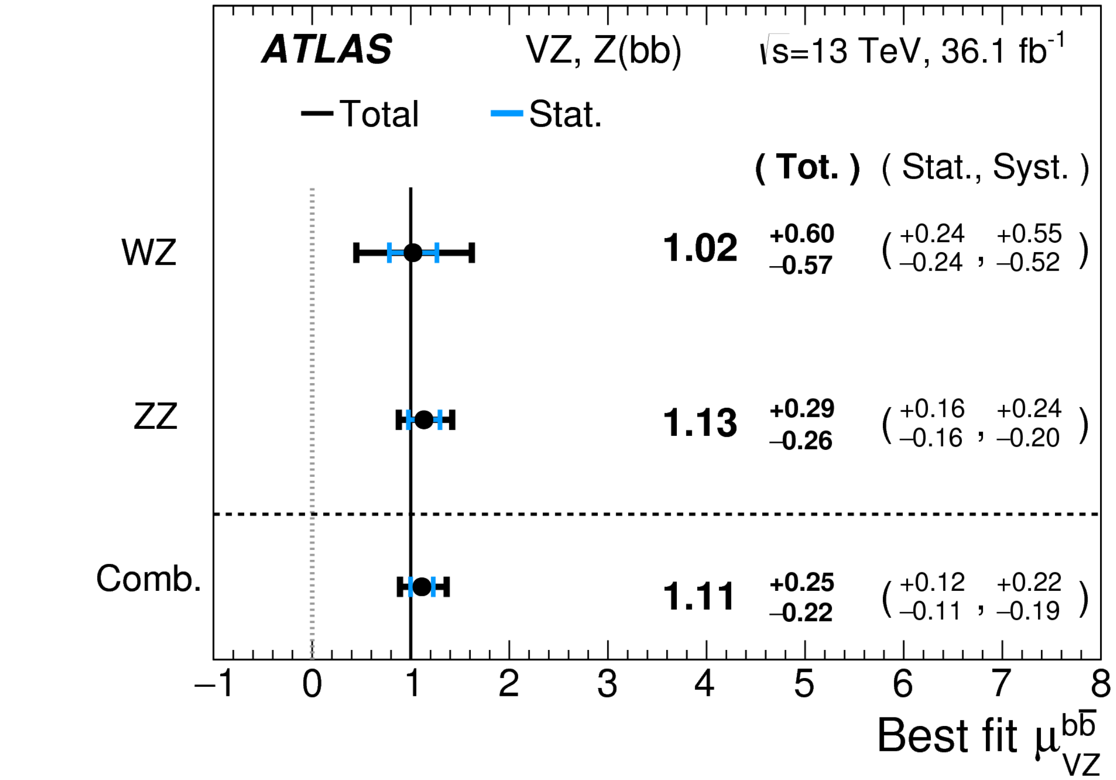
signal modelling	0.17
statistics in MC	0.13
b-tagging	0.11

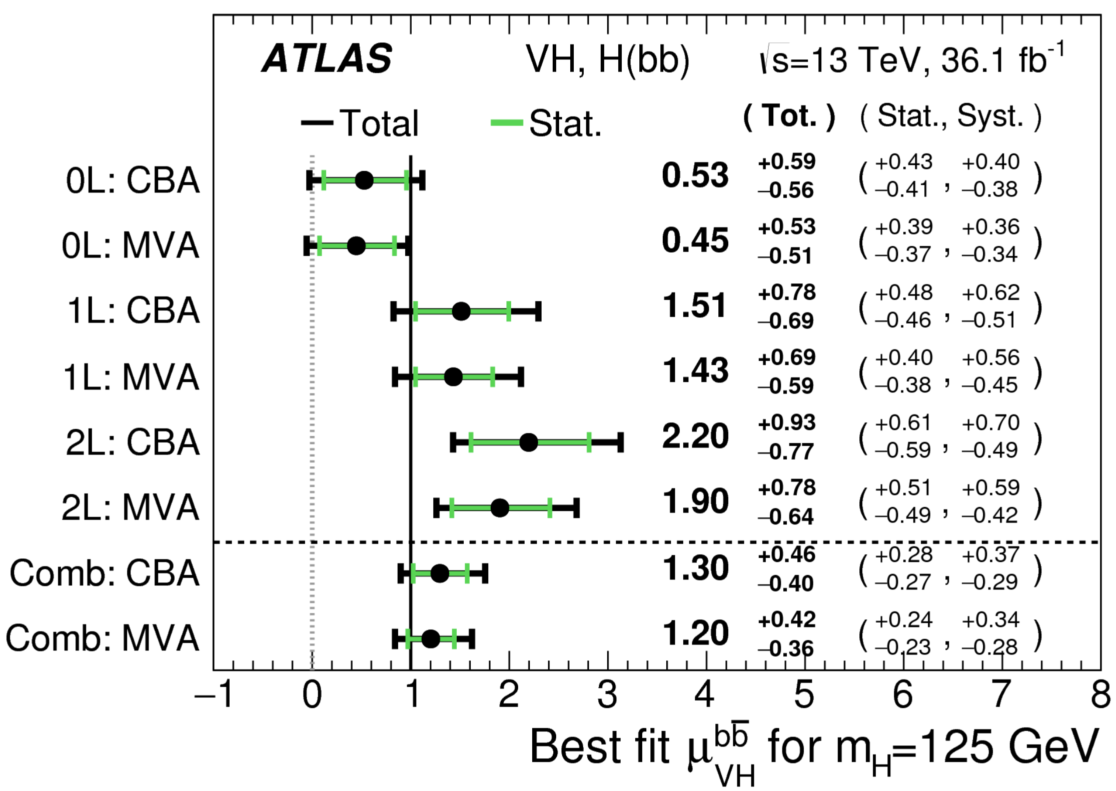
Driven by theory uncertainties: needs external input

Under experimental control: can be improved within ATLAS

Evidence for VH, H→bb: crosschecks

The **VZ, Z→bb data sample is used to validate the analysis** procedure

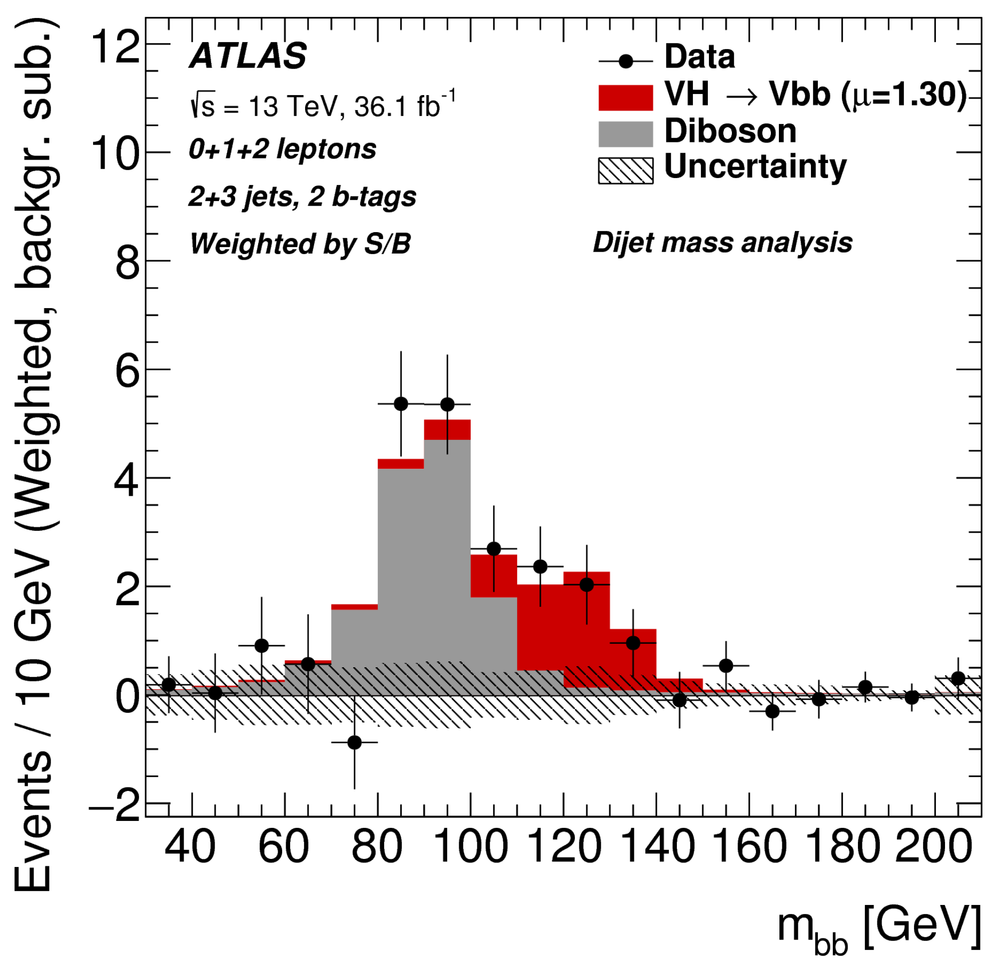




Result is compatible with already measured SM WZ and ZZ production **within 1σ**

Observed significance: 5.8σ

Results compared with **cut-based analysis**, which also **adopts invariant mass as main discriminant**



Search for ZH, H→cc

Most challenging decay channel presented here; **suffers from large backgrounds** and relies on the **subtle discrimination of charm jets** from light and beauty jets

Analysis focuses on
Z decays to two leptons

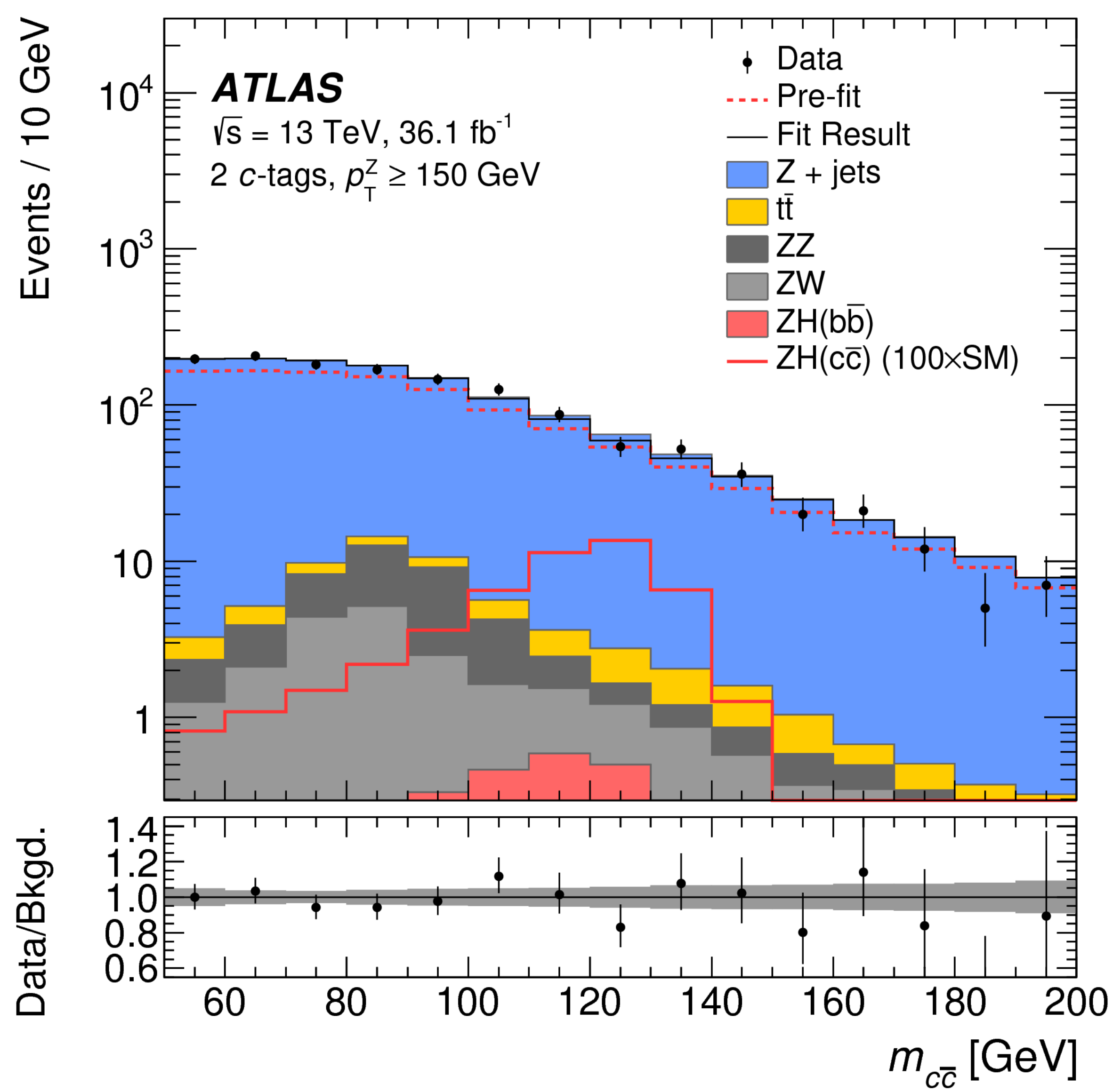
Data divided in **four categories:**
Z p_T and number of c-tags

Dijet invariant mass used as discriminating variable

Simultaneous fit in all categories, **extracting signal yield and Z+jets normalisation**

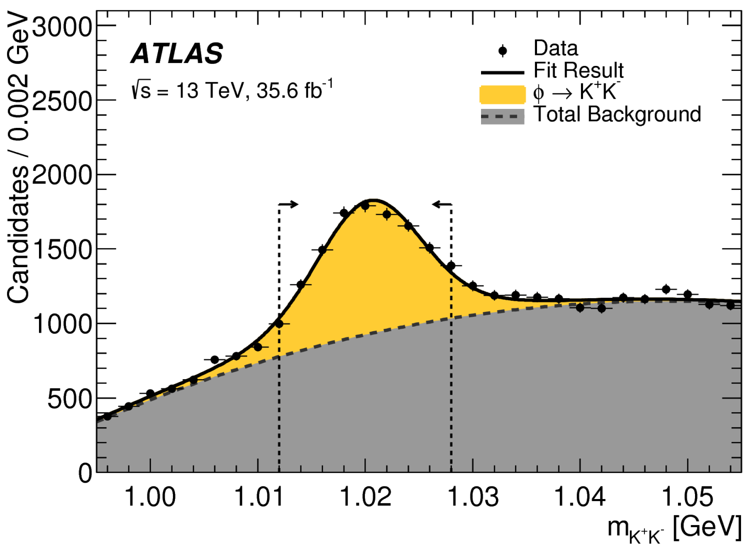
Source	$\sigma/\sigma_{\mathrm{tot}}$
Statistical	**49%**
Floating $Z+$jets normalization	31%
Systematic	**87%**
Flavor tagging	73%
Background modeling	47%
Lepton, jet and luminosity	28%
Signal modeling	28%
MC statistical	6%

95% upper limits
Observed: 110 x SM
Expected: 150 x SM



Search for Z/H→ϕ/ρ+gamma

Not a direct measurement of fermionic Higgs decays, but **sensitive to light quarks coupling;** requires a much larger dataset than the currently available one



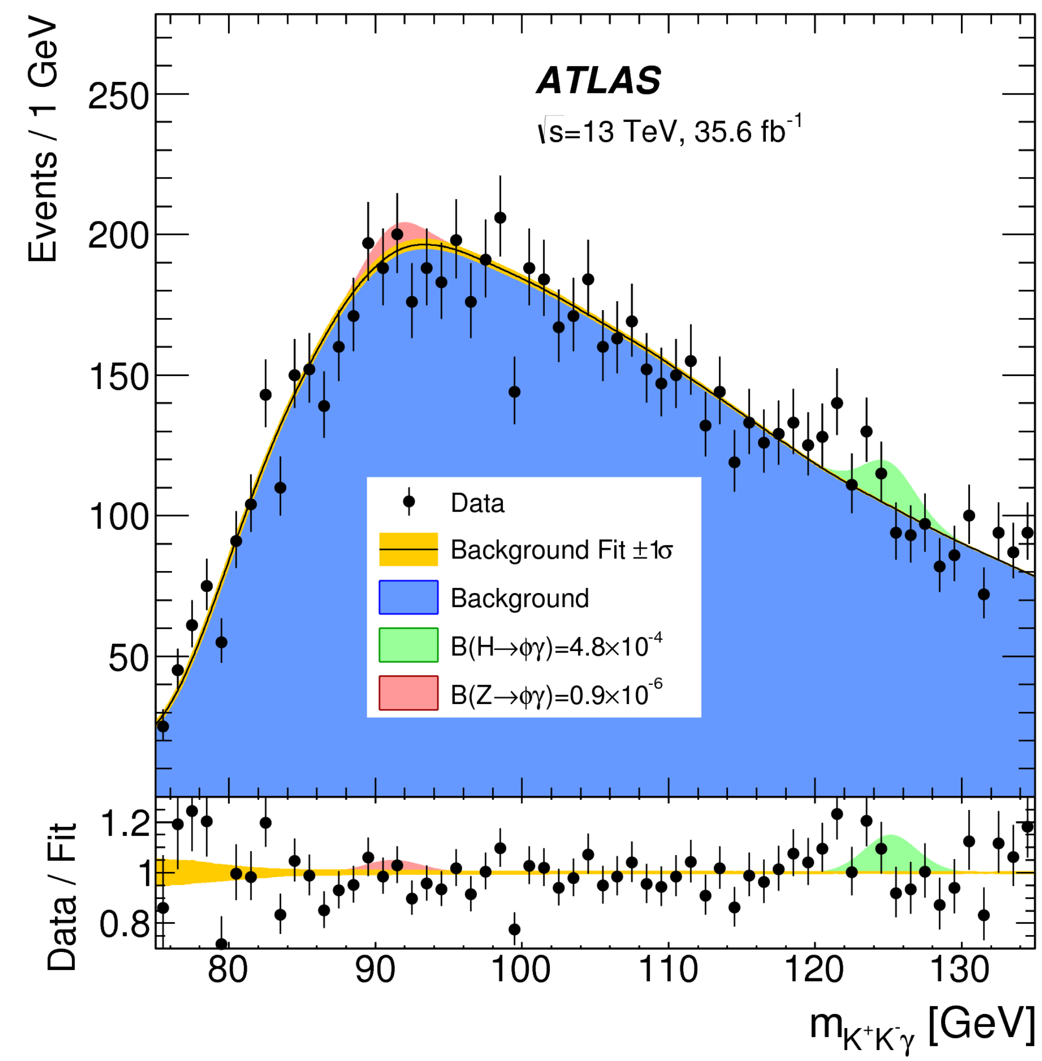
Branching Fraction Limit (95% CL)	Expected	Observed	
$\mathcal{B}(H \to \phi\gamma)\,[\,10^{-4}\,]$	$4.2^{+1.8}_{-1.2}$	4.8	208 x SM
$\mathcal{B}(Z \to \phi\gamma)\,[\,10^{-6}\,]$	$1.3^{+0.6}_{-0.4}$	0.9	87 x SM
$\mathcal{B}(H \to \rho\gamma)\,[\,10^{-4}\,]$	$8.4^{+4.1}_{-2.4}$	8.8	52 x SM
$\mathcal{B}(Z \to \rho\gamma)\,[\,10^{-6}\,]$	33^{+13}_{-9}	25	597 x SM

Pair of **opposite sign tracks** used to reconstruct and select **ϕ/ρ meson mass**

Main backgrounds:
gamma+jets and dijets

Data-driven background estimate generated from control regions

Bkg normalisation and shape extracted from fit to data



CONCLUSIONS

Many results on fermionic decays of the Higgs boson, based on 7, 8, 13 TeV data published by ATLAS

Actually much more material than what can fit in this talk!
Focus has been given to Run 2 results with data recorded at 13 TeV

Thanks to the continuous effort put in flavour tagging performance and calibration, **ATLAS assessed evidence for $H\rightarrow bb$ decays**, which is likely to become an observation with the full Run 2 dataset!

One more search is possibly within reach for Run 2, combining all LHC data: this is the case of the **search for 2nd generation leptons via $H\rightarrow\mu^+\mu^-$ decays**

Other searches will require high luminosity LHC data to be accessible:

- **first inclusive search for $H\rightarrow cc$**
- **search for decays to elusive 1st/2nd generation quarks $H\rightarrow\phi/\rho$+gamma**

Rapidly increasing LHC dataset will further enhance our knowledge of the fermionic Higgs decays

BACKUP

Extra info - H→$\mu^+\mu^-$

For jet-related variables, only the two jets with highest p_T are considered, with the leading (subleading) jet denoted by $j_1(j_2)$. Among those variables, the most sensitive ones are dijet invariant mass (m_{jj}), $p_T^{\mu\mu}$, difference in pseudorapidity $\Delta\eta_{jj}$, and angular distance ΔR_{jj} between the two jets.

Other variables with less discriminating power include transverse momentum of the dijet system (p_T^{jj}), E_T^{miss}, scalar p_T sum of muons and jets (S_T), p_T of the system containing two muons and one or two jets ($p_T^{\mu\mu j_1}$, $p_T^{\mu\mu j_2}$, and $p_T^{\mu\mu jj}$), rapidity difference between the dimuon system and the jets ($\Delta y_{\mu\mu,j_1}$, $\Delta y_{\mu\mu,j_2}$, and $\Delta y_{\mu\mu,jj}$), and "centrality", defined as the difference between the dimuon rapidity and the averaged jet rapidity divided by the absolute rapidity difference between j_1 and j_2.

Extra info - H→μ+μ-

	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

Extra info - H→bb

Process	ME generator	ME PDF	PS and Hadronisation	UE model tune	Cross-section order	ace2.5cm
Signal						
$qq \to WH \to \ell\nu b\bar{b}$	Powheg-Box v2 [19] + GoSam [22] + MiNLO [23,24]	NNPDF3.0NLO$^{(\star)}$ [20]	Pythia8.212 [13]	AZNLO [21]	NNLO(QCD)+ NLO(EW) [25,26,27,28,29,30,31]	
$qq \to ZH \to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	Powheg-Box v2 + GoSam + MiNLO	NNPDF3.0NLO$^{(\star)}$	Pythia8.212	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$^{(\star)}$	Pythia8.212	AZNLO	NLO+ NLL [32,33,34,35,36]	
Top quark						
$t\bar{t}$	Powheg-Box v2 [37]	NNPDF3.0NLO	Pythia8.212	A14 [38]	NNLO+NNLL [39]	
s-channel	Powheg-Box v1 [40]	CT10 [41]	Pythia6.428 [42]	P2012 [43]	NLO [44]	
t-channel	Powheg-Box v1 [40]	CT10f4	Pythia6.428	P2012	NLO [45]	
Wt	Powheg-Box v1 [46]	CT10	Pythia6.428	P2012	NLO [47]	
Vector boson + jets						
$W \to \ell\nu$	Sherpa 2.2.1 [16,48,49]	NNPDF3.0NNLO	Sherpa 2.2.1 [50,51]	Default	NNLO [52]	
$Z/\gamma^* \to \ell\ell$	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						
WW	Sherpa 2.1.1	CT10	Sherpa 2.1.1	Default	NLO	
WZ	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO	
ZZ	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO	

Extra info - H→bb

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

Extra info - H→bb

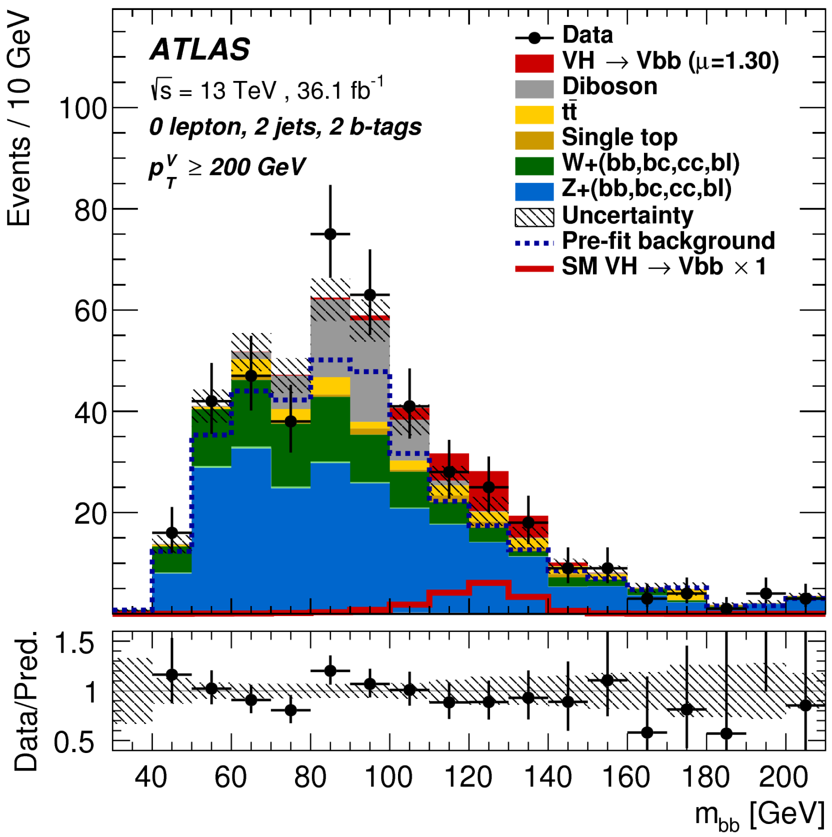
Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	$\times$	$\times$
E_T^{miss}	$\times$	$\times$	$\times$
$p_T^{b_1}$	$\times$	$\times$	$\times$
$p_T^{b_2}$	$\times$	$\times$	$\times$
m_{bb}	$\times$	$\times$	$\times$
$\Delta R(\vec{b}_1, \vec{b}_2)$	$\times$	$\times$	$\times$
$\lvert\Delta\eta(\vec{b}_1, \vec{b}_2)\rvert$	$\times$		
$\Delta\phi(\vec{V}, \vec{bb})$	$\times$	$\times$	$\times$
$\lvert\Delta\eta(\vec{V}, \vec{bb})\rvert$			$\times$
m_{eff}	$\times$		
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		$\times$	
m_T^W		$\times$	
$m_{\ell\ell}$			$\times$
m_{top}		$\times$	
$\lvert\Delta Y(\vec{V}, \vec{bb})\rvert$		$\times$	
	Only in 3-jet events		
$p_T^{\mathrm{jet}_3}$	$\times$	$\times$	$\times$
m_{bbj}	$\times$	$\times$	$\times$

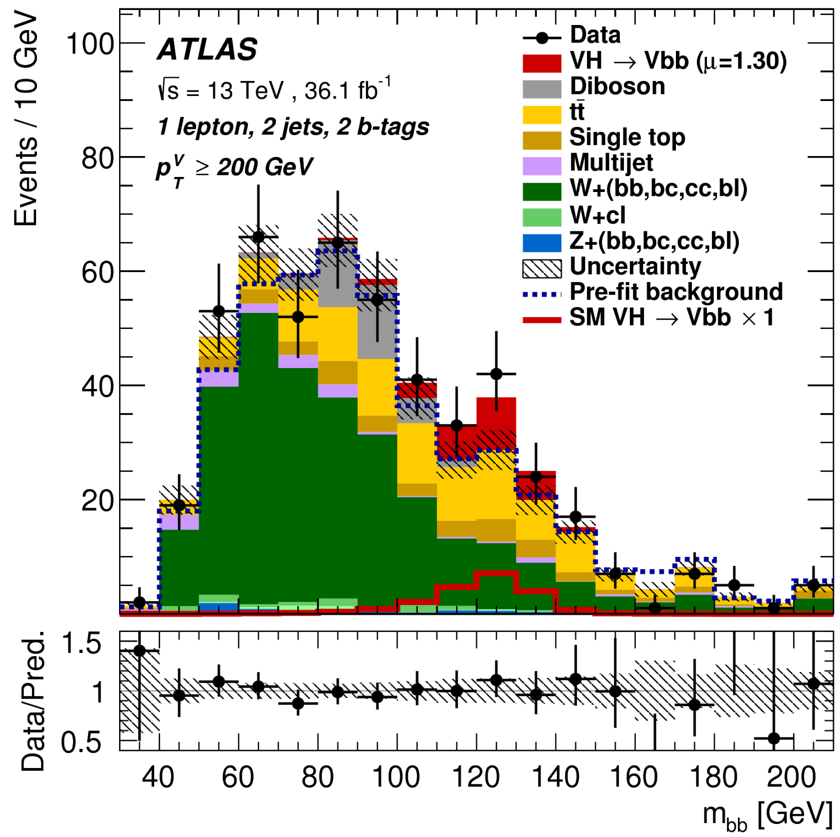
Extra info - H→bb

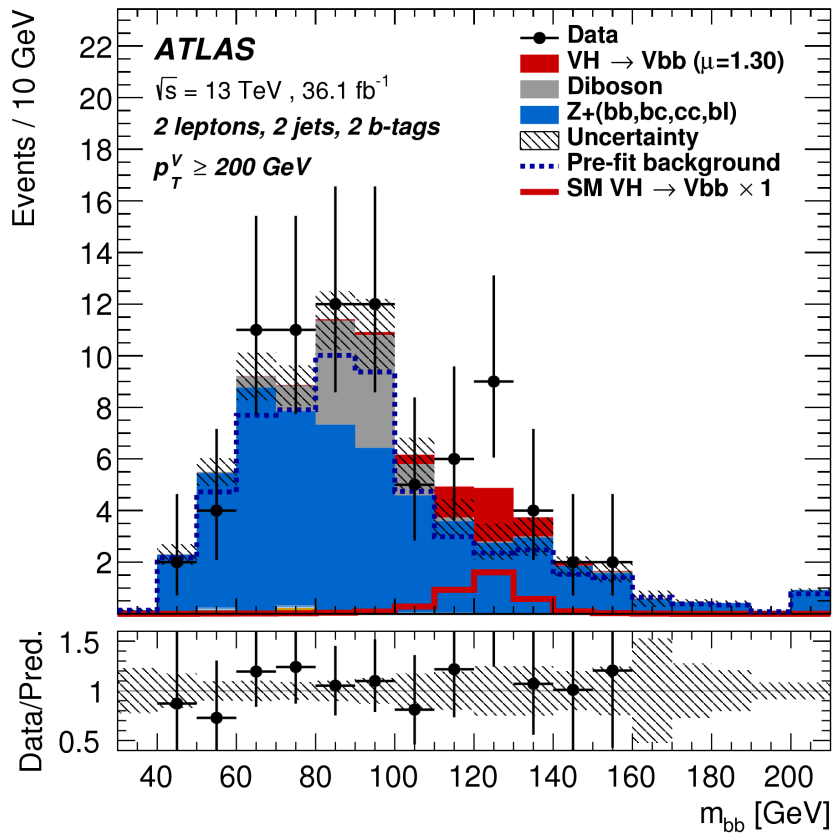
Process	Normalisation factor
$t\bar{t}$ 0- and 1-lepton	0.90 ± 0.08
$t\bar{t}$ 2-lepton 2-jet	0.97 ± 0.09
$t\bar{t}$ 2-lepton 3-jet	1.04 ± 0.06
W + HF 2-jet	1.22 ± 0.14
W + HF 3-jet	1.27 ± 0.14
Z + HF 2-jet	1.30 ± 0.10
Z + HF 3-jet	1.22 ± 0.09

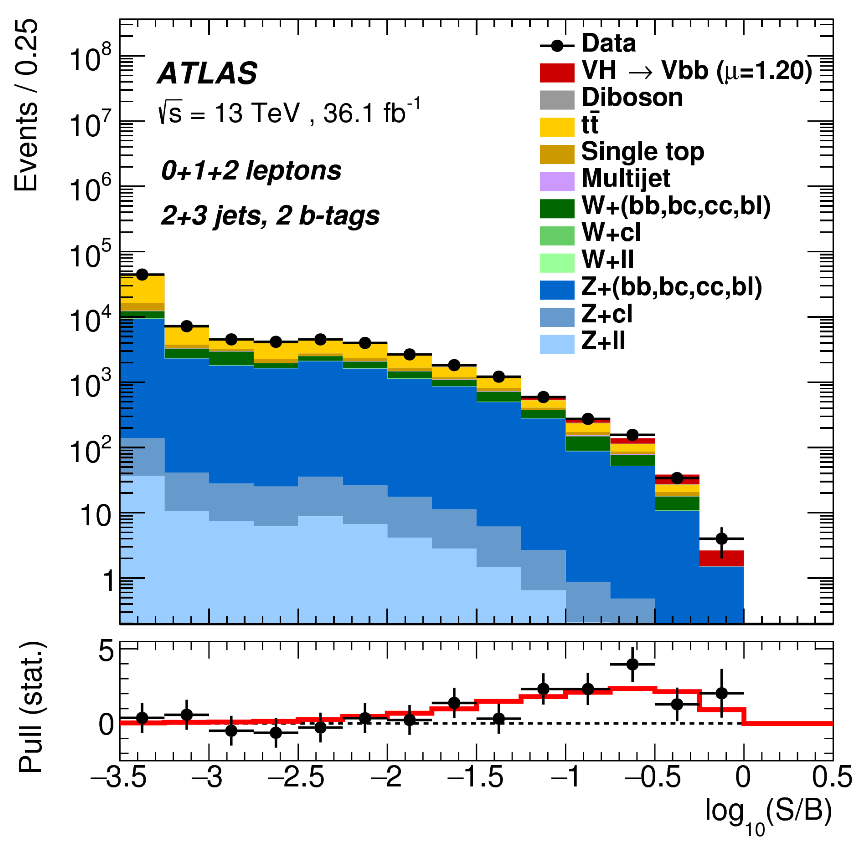
Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
E_T^{miss}		0.03
Leptons		0.01
b-tagging	b-jets	0.09
	c-jets	0.04
	light jets	0.04
	extrapolation	0.01
Pile-up		0.01
Luminosity		0.04
Theoretical and modelling uncertainties		
Signal		0.17
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

Extra info - H→bb





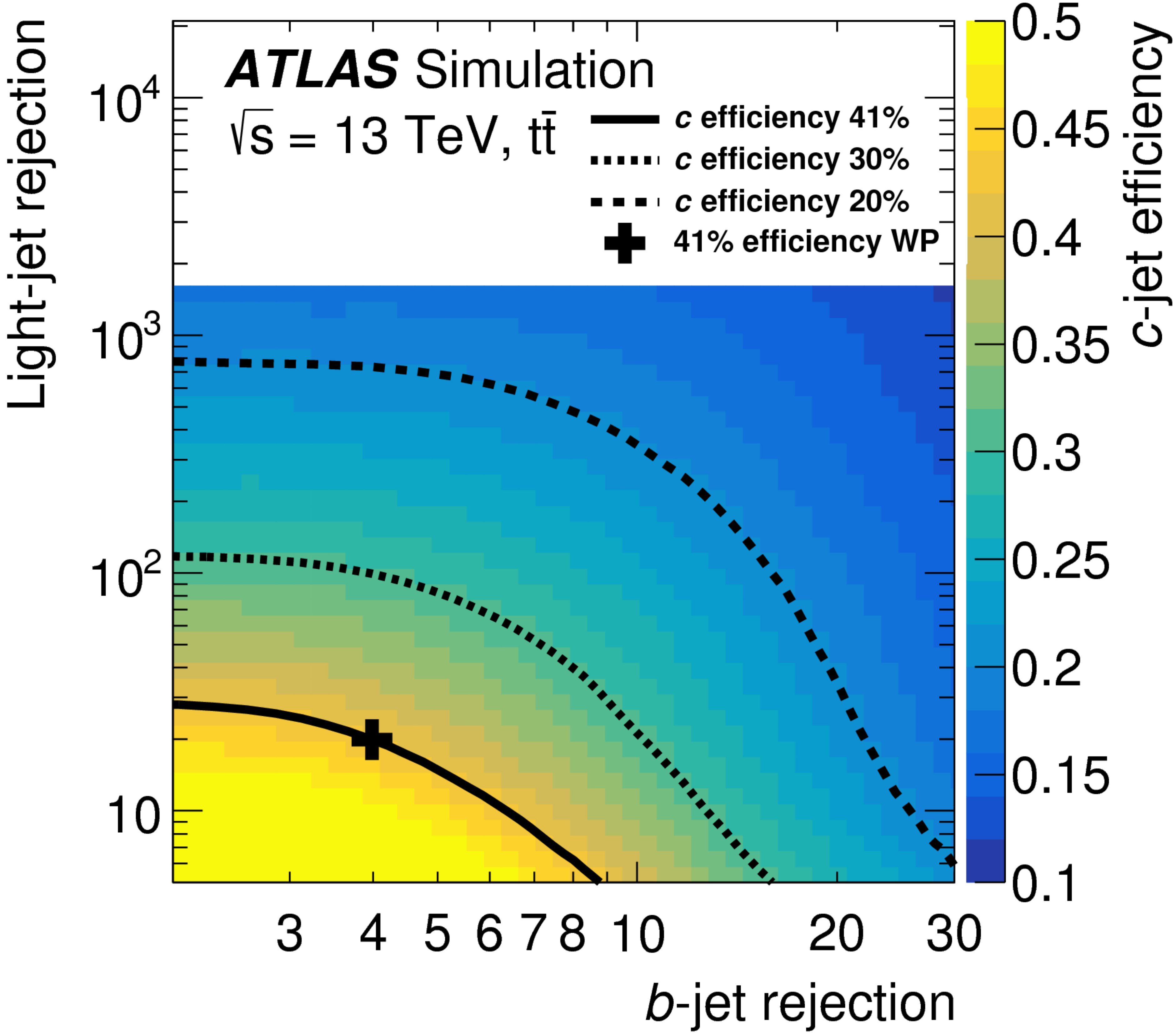




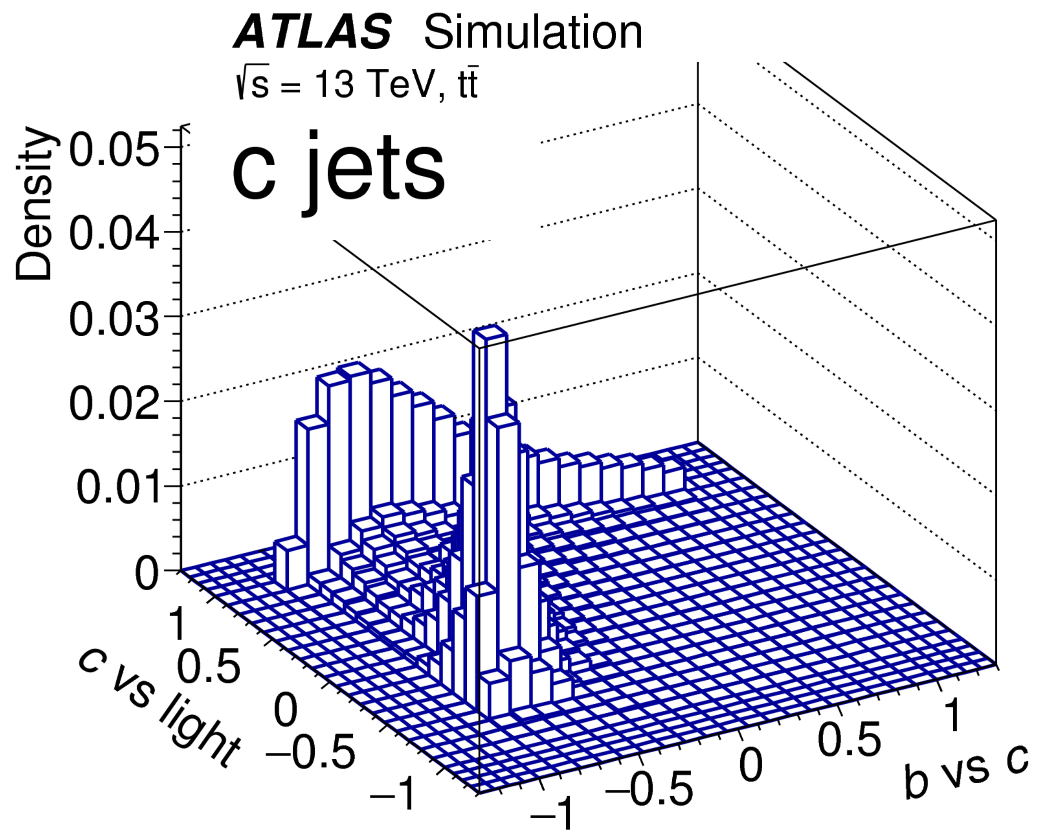
Extra info - H→cc

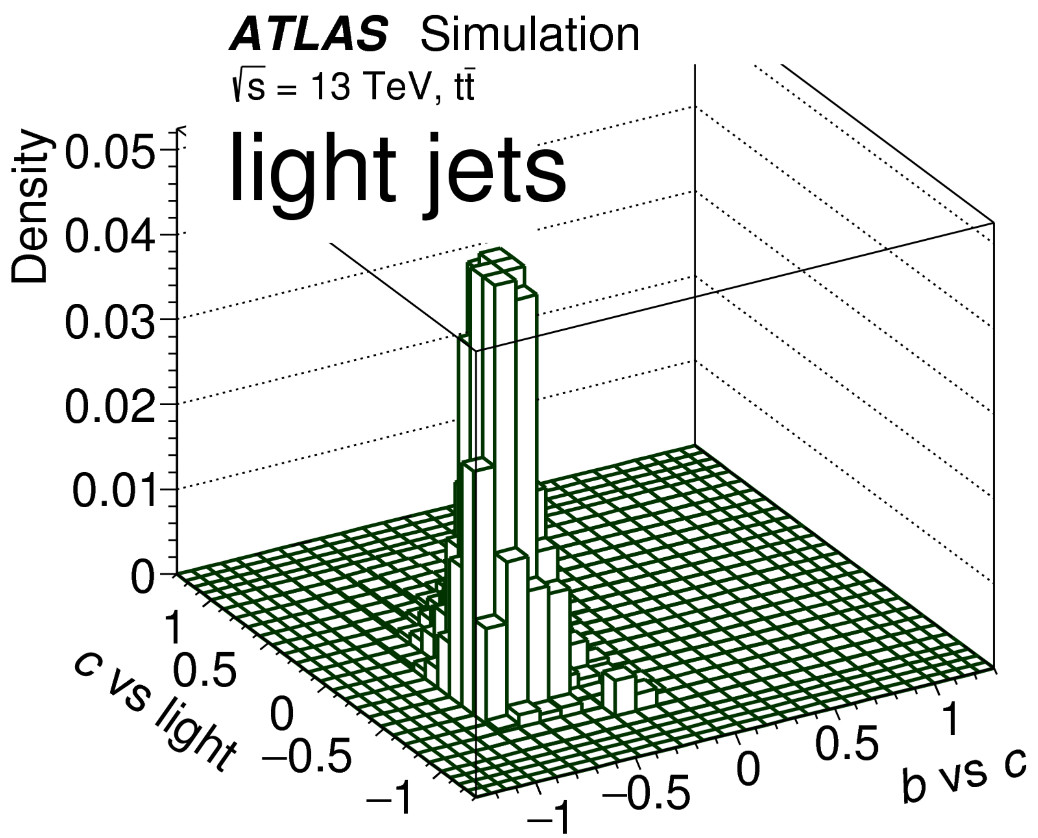
Process	Event Generator (alternative)	Parton Shower (alternative)	PDF (alternative)	Tune	Cross-section
$q\bar{q} \to ZH$	POWHEG-BOX v2 [28] +GOSAM [35] +MINLO [45,46]	PYTHIA 8 (HERWIG 7 [47])	PDF4LHC15NLO [33] /CTEQ6L1 [36,37]	AZNLO [34] (A14 [48])	NNLO (QCD)* +NLO (EW) [38,39,40,41,42,43,44]
$gg \to ZH$	POWHEG-BOX v2	PYTHIA 8 (HERWIG 7)	PDF4LHC15NLO /CTEQ6L1	AZNLO (A14)	NLO+NLL (QCD) [49,50,51,15]
$t\bar{t}$	POWHEG-BOX v2	PYTHIA 8 (HERWIG 7)	NNPDF3.0NLO [52] /NNPDF2.3LO	A14	NNLO+NNLL [53]
ZW, ZZ	SHERPA 2.2.1 [29] (POWHEG-BOX)	SHERPA (PYTHIA 8)	NNPDF3.0NNLO	SHERPA	NLO
Z+jets	SHERPA 2.2.1 (MG5_AMC)	SHERPA (PYTHIA 8)	NNPDF3.0NNLO (NNPDF2.3LO)	SHERPA (A14)	NNLO [54]

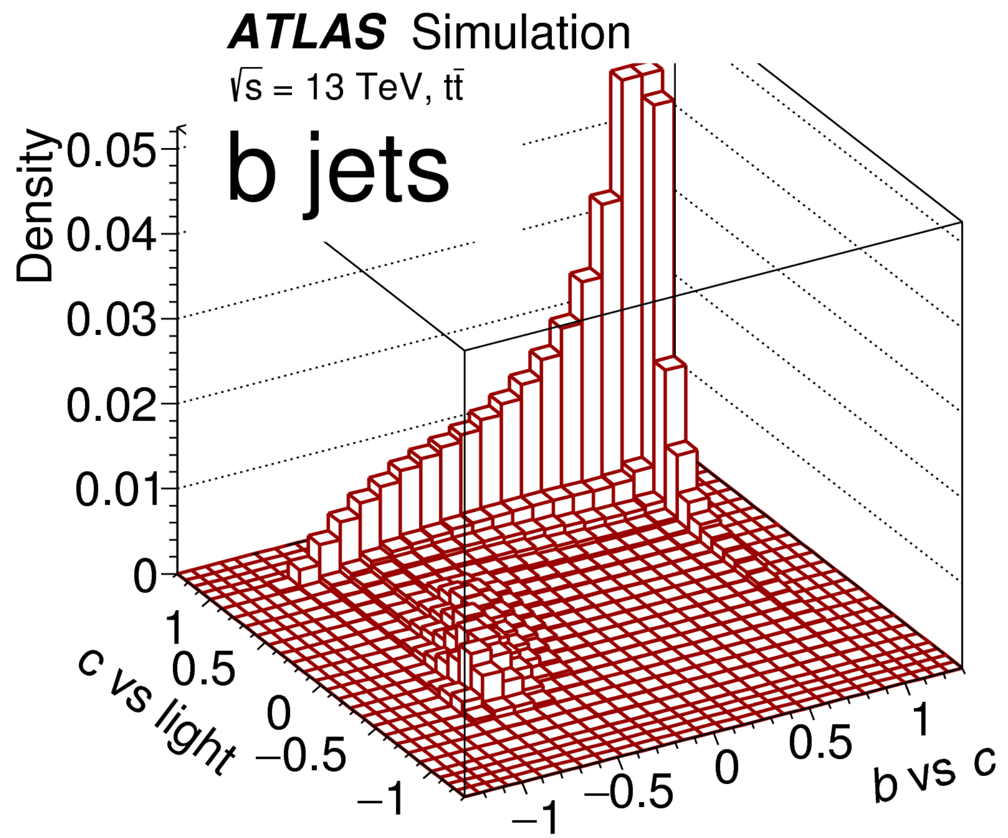
Extra info - H→cc



Extra info - H→cc







Extra info - H→ϕ/ρ+gamma

Source of systematic uncertainty	Yield uncertainty
Total H cross section	6.3%
Total Z cross section	2.9%
Integrated luminosity	3.4%
Photon ID efficiency	2.5%
Trigger efficiency	2.0%
Tracking efficiency	6.0%

	Observed yields (Mean expected background)					Expected signal yields	
	Mass range [GeV]					H	Z
	All	81–101		120–130		$[\mathcal{B} = 10^{-4}]$	$[\mathcal{B} = 10^{-6}]$
$\phi\gamma$	12051	3364	(3500 ± 30)	1076	(1038 ± 9)	15.6 ± 1.5	83 ± 7
$\rho\gamma$	58702	12583	(12660 ± 60)	5473	(5450 ± 30)	17.0 ± 1.7	7.5 ± 0.6