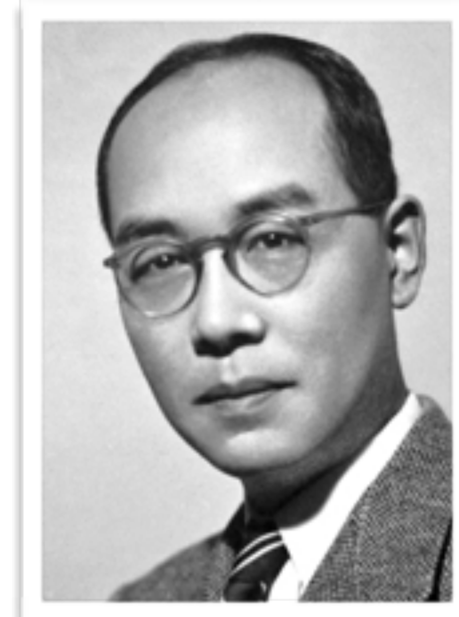
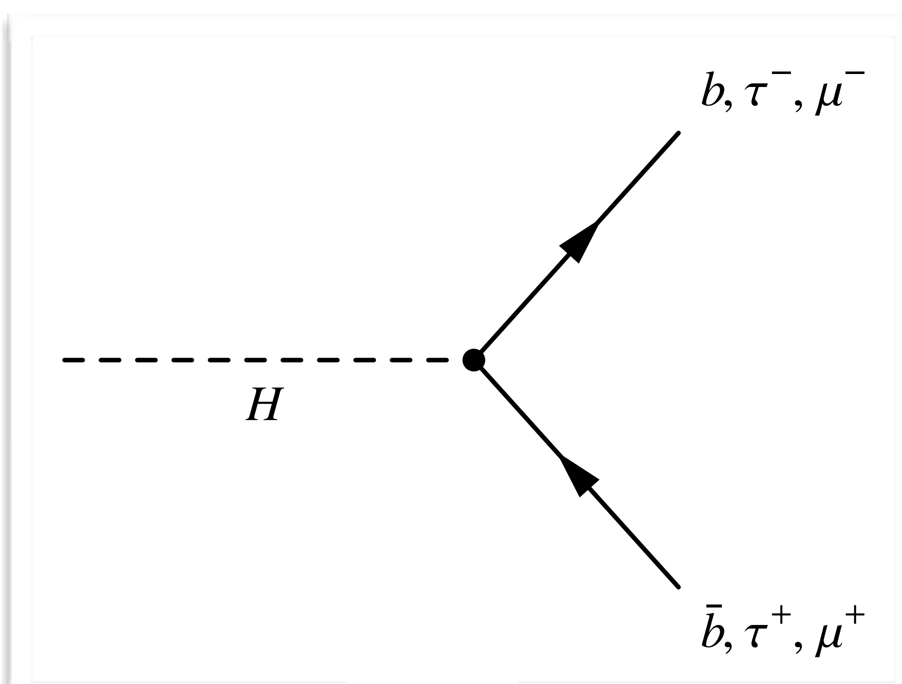


Higgs boson interactions with the Yukawa sector from ATLAS

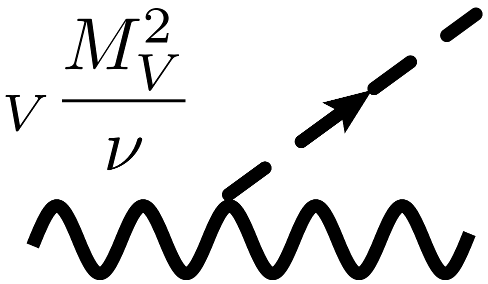
Heather M. Gray, CERN
on behalf of the ATLAS Collaboration



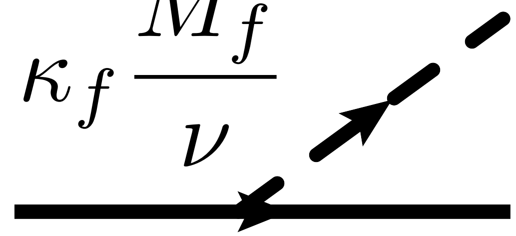
Introduction

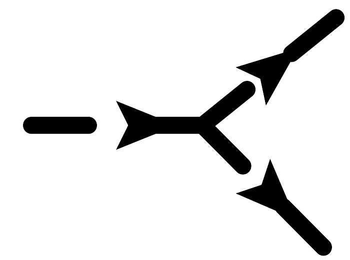
- Tree-level terms in the SM Lagrangian for the SM $J^{PC} = 0^{++}$ Higgs

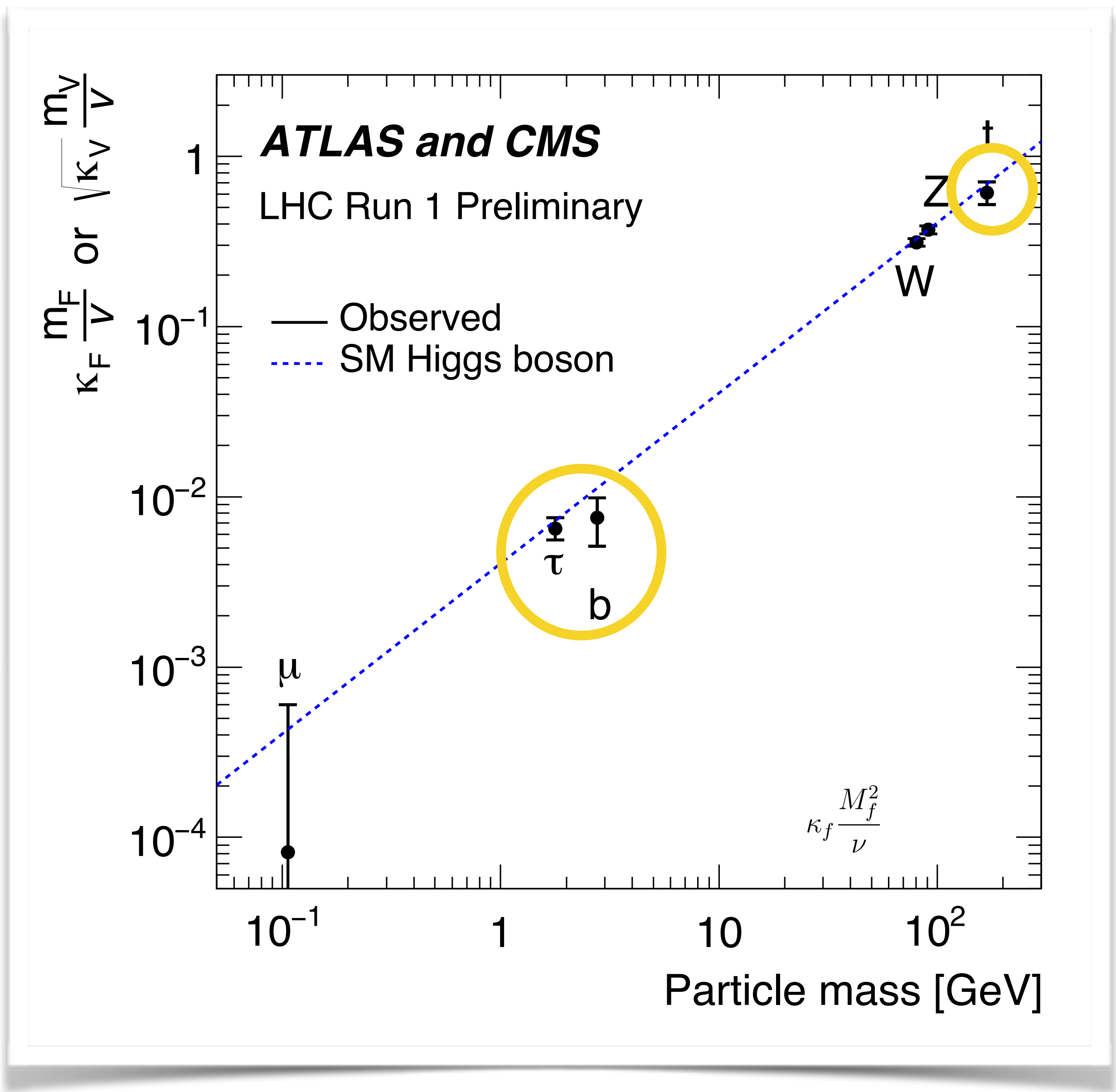
$\kappa_V \frac{M_V^2}{\nu}$



$\kappa_f \frac{M_f}{\nu}$







Higgs Decays to Fermions with ATLAS in Run-1

Decay Channel	Branching Ratio	ATLAS Run-1 μ
bb*	57.5 ± 1.9	0.6±0.4[2]
WW	21.6 ± 0.9	
gg	8.56 ± 0.86	
ττ	6.3 ± 0.36	1.4±0.4
cc	2.9 ± 0.35	
ZZ	2.67 ± 0.11	
γγ	0.228 ± 0.011	
Zγ	0.155 ± 0.014	
μμ	0.022 ± 0.001	0.7±3.6
…		
J/ψγ	$(2.8 \pm 0.2) \times 10^{-4}$	< O(1000) x SM

ttH results not discussed here: see Valerio Dao's talk tomorrow morning

[1]Tevatron: σ(VH(bb) = 0.19 ± 0.09 pb [2]Includes ttH [3]Includes WW

τ

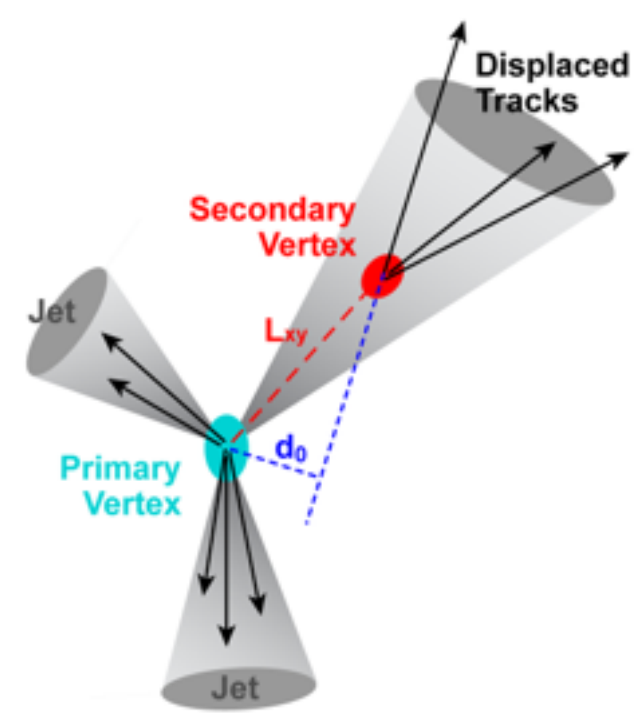
- 3 channels (lep-lep, lep-had, had-had)
- Two categories (VBF, boost)
- Main challenges are mass resolution, triggering (had-had) and controlling the Z->ττ and multijet backgrounds

b

- Associated production with a vector boson
- 3 channels (0, 1, 2-lepton)
- Categories in p_T^V, number of jets and b-tag purity
- Challenges include mass resolution and ttbar, V+jets and multijet backgrounds

μ

- Two oppositely charged muons, $p_T > 25, 15$ GeV, $E_T^{miss} < 80$ GeV
- 1 channel
- 7 categories
- Challenges include small branching ratio and control of the Z background



See Daniel Büscher’s talk on VH(bb) on Wednesday afternoon

Categories

- Most LHC Higgs analyses use categories to improve sensitivity
- Main strategy is to separate events with different significance ~S/√B

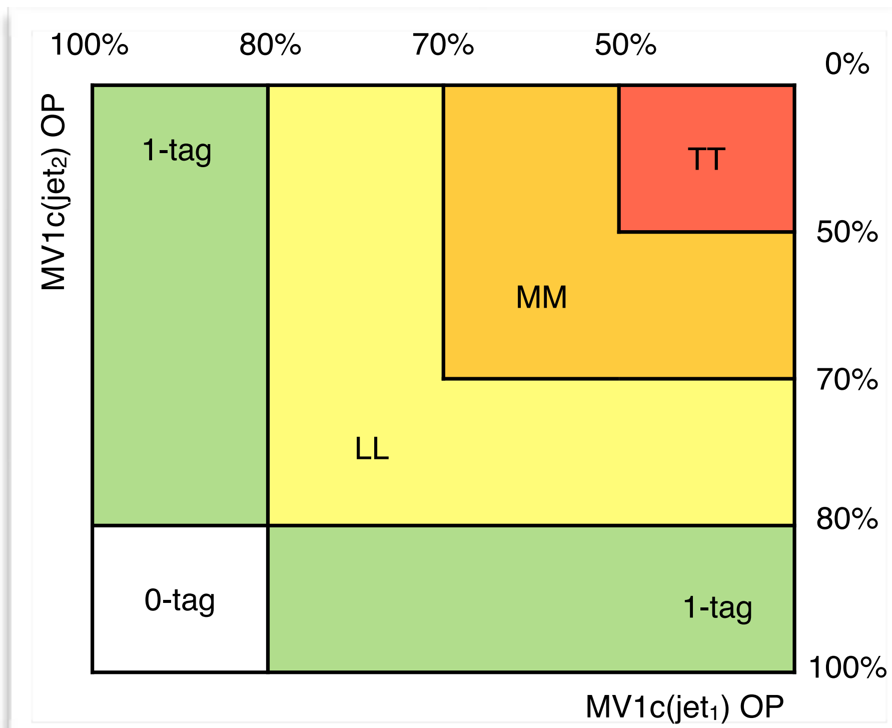
$$\sqrt{\frac{S_1^2}{B1}+\frac{S_2^2}{B_2}} >> \frac{S_1+S_2}{\sqrt{B_1+B_2}}$$

- Differences can depend on resolution, background type or size, signal production mechanism or systematic uncertainties
- μ,τ : 7 categories
- b: 38 categories

μμ categories

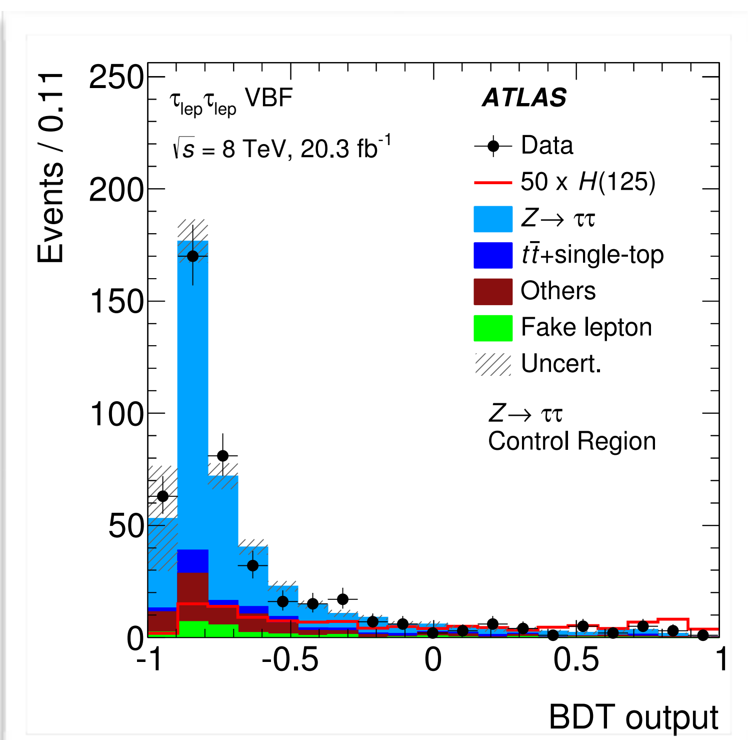
$\sqrt{s}$ [TeV]	Category	N_S	$\frac{N_S}{\sqrt{N_B}}$	FWHM [GeV]	χ^2/ndof
8	non-cen. low $p_T^{\mu^+\mu^-}$	6.1	0.07	6.6	49.8/48
8	cen. low $p_T^{\mu^+\mu^-}$	2.6	0.06	5.5	52.8/48
8	non-cen. medium $p_T^{\mu^+\mu^-}$	10.4	0.15	6.6	45.1/48
8	cen. medium $p_T^{\mu^+\mu^-}$	4.7	0.13	5.6	36.7/48
8	non-cen. high $p_T^{\mu^+\mu^-}$	5.5	0.13	7.2	26.7/48
8	cen. high $p_T^{\mu^+\mu^-}$	2.6	0.10	6.0	32.3/48
8	VBF	0.8	0.09	7.0	18.6/19
7	non-cen. low $p_T^{\mu^+\mu^-}$	1.0	0.03	6.8	42.0/48
7	cen. low $p_T^{\mu^+\mu^-}$	0.5	0.03	5.3	43.5/48
7	non-cen. medium $p_T^{\mu^+\mu^-}$	1.8	0.06	6.9	41.2/48
7	cen. medium $p_T^{\mu^+\mu^-}$	0.8	0.05	5.5	34.4/48
7	non-cen. high $p_T^{\mu^+\mu^-}$	0.9	0.05	7.5	60.0/48
7	cen. high $p_T^{\mu^+\mu^-}$	0.5	0.05	5.9	56.2/48

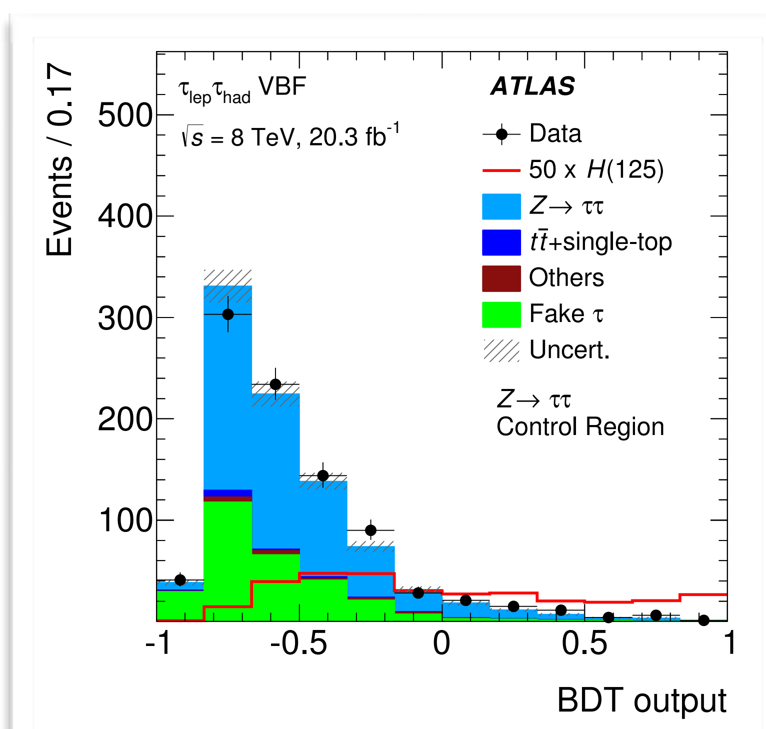
b tagging categories

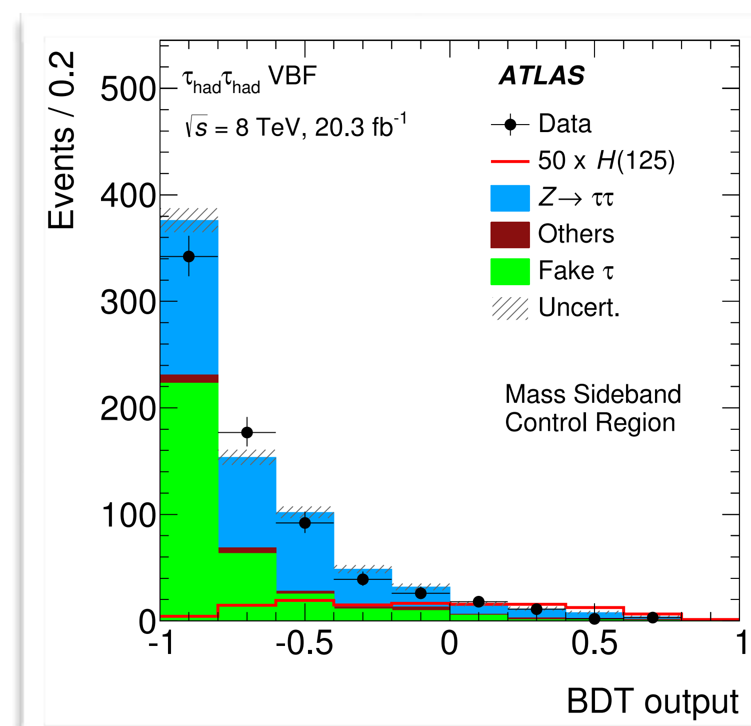


ττ Categories

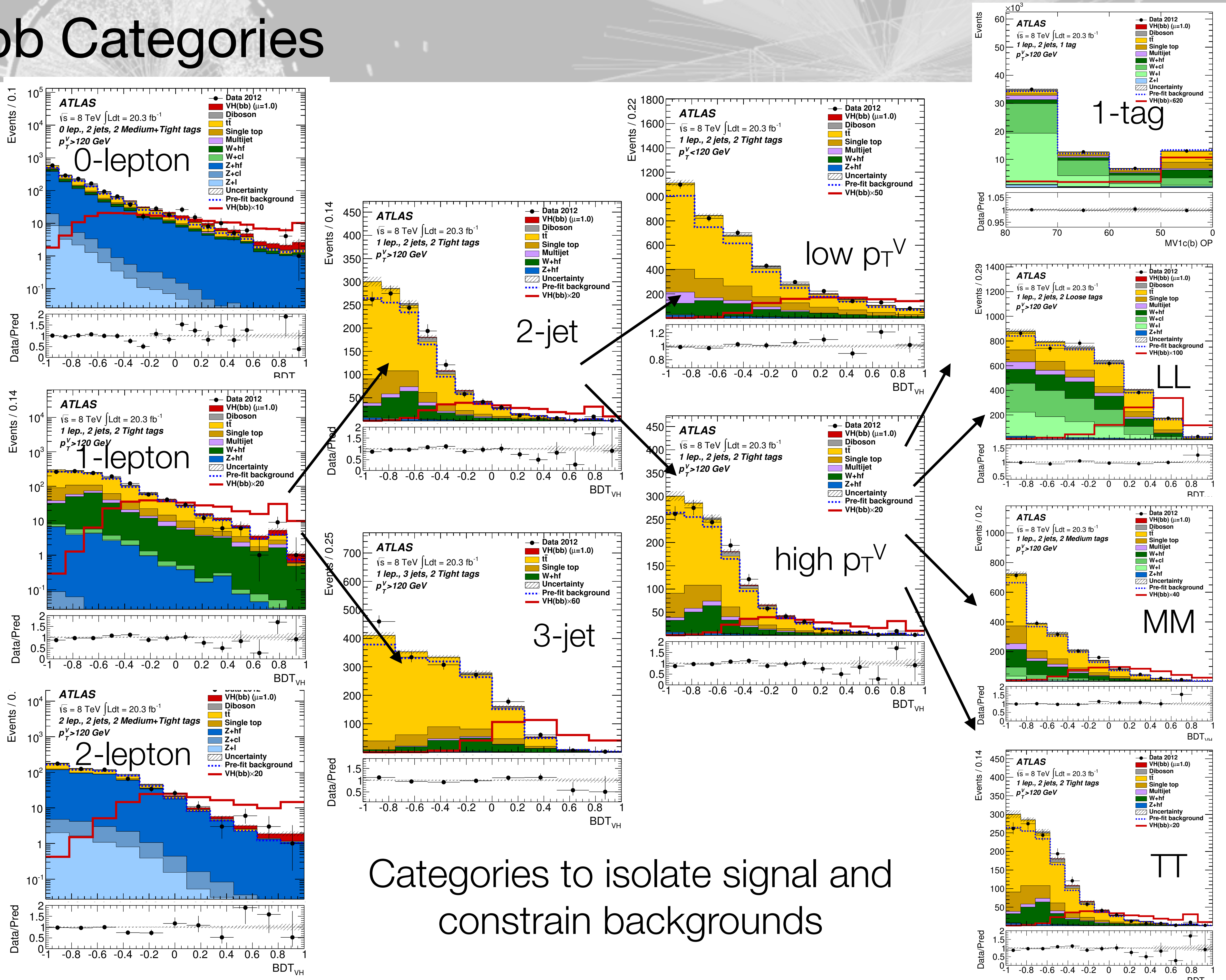
	VBF	Boost	Rest
lep-lep	$p_T^j > 40, 30$ GeV $\Delta\eta_{jj} > 2.2$	Fail VBF $p_T^H > 100$ GeV	
lep-had	$p_T^j > 50, 30$ GeV $\Delta\eta_{jj} > 3$		
had-had	$p_T^j > 50, 30$ GeV $\Delta\eta_{jj} > 2$		Fail VBF, Boost







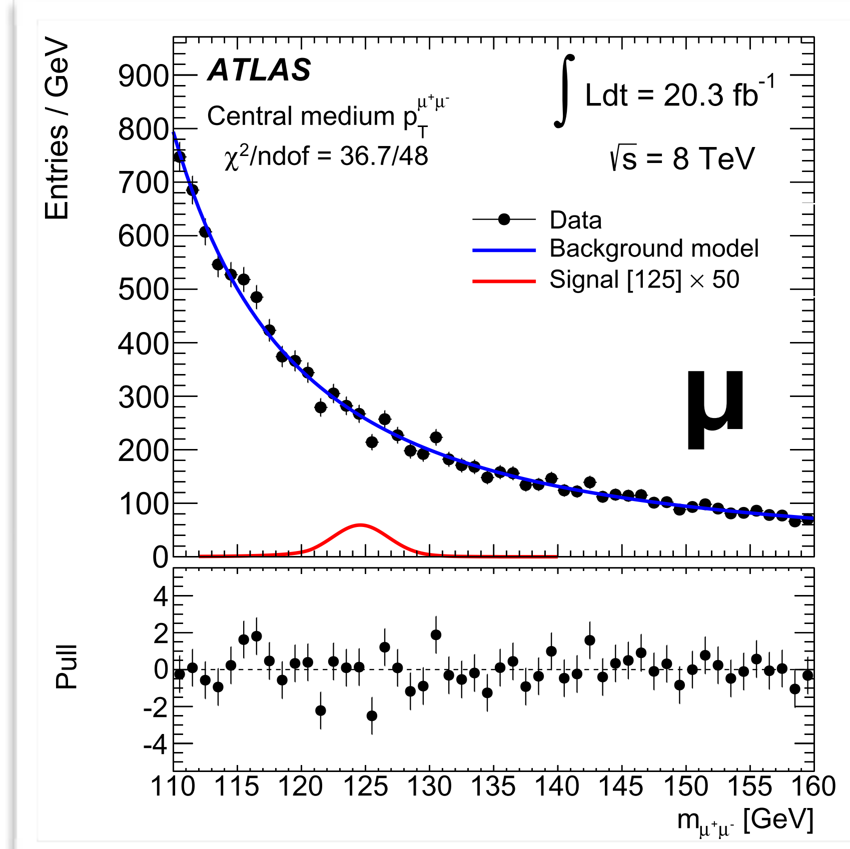
bb Categories

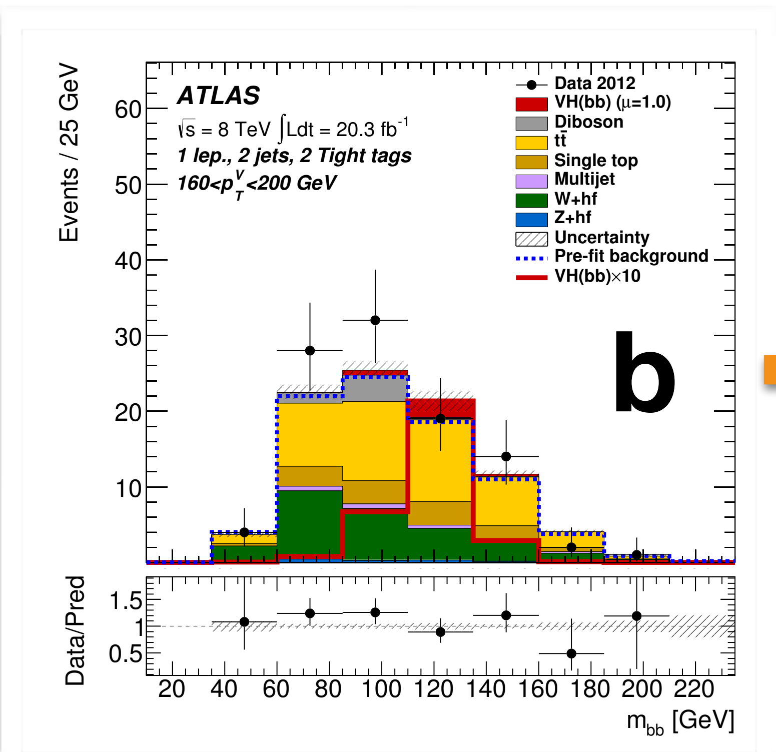


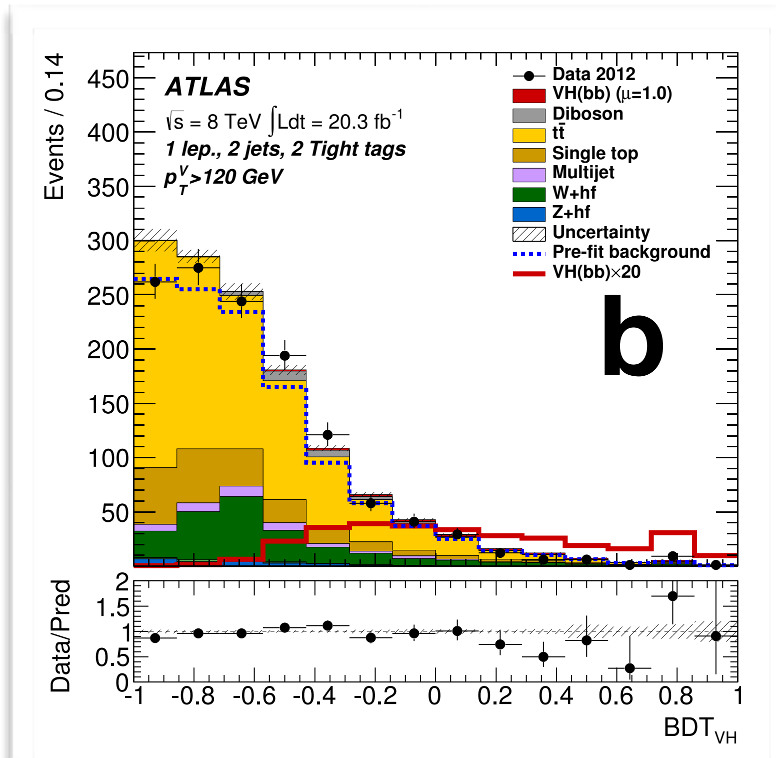
Categories to isolate signal and constrain backgrounds

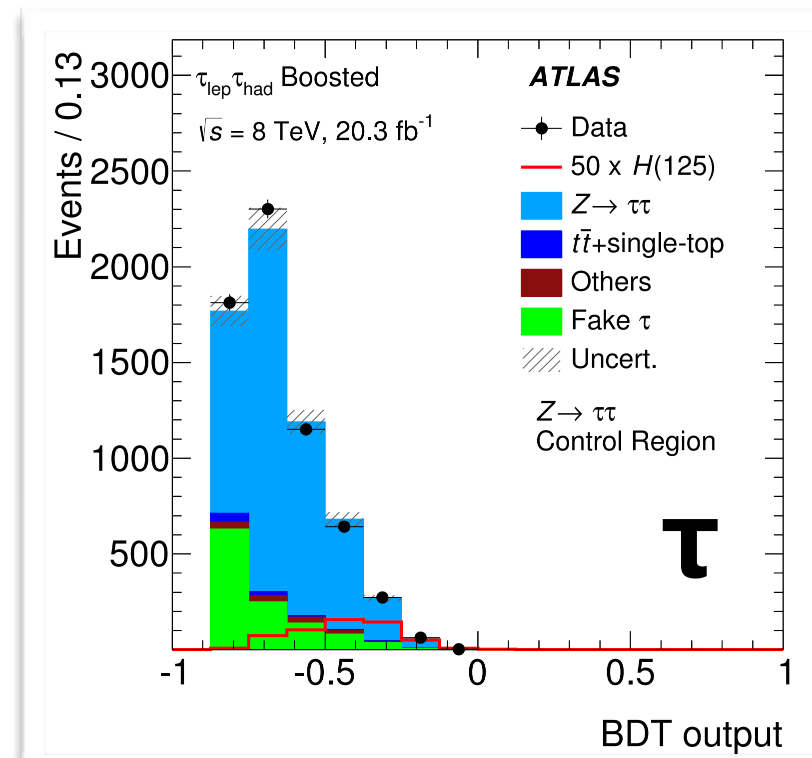
Signal Extraction

- Key discriminating quality of the Higgs is the mass
- For μ, perform fit to signal and background
- Gain sensitivity for b and τ by constructing a boosted decision tree (BDT) from many kinematic variables, optimise on S/B
    - ~20-30% sensitivity improvement for bb and ττ









BDT Variables

bb Variables

Variable	0-Lepton	1-Lepton	2-Lepton
p_{T}^{V}		×	×
$E_{\mathrm{T}}^{\mathrm{miss}}$	×	×	×
$p_{\mathrm{T}}^{b_1}$	×	×	×
$p_{\mathrm{T}}^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\|\Delta\eta(b_1, b_2)\|$	×		×
$\Delta\phi(V, bb)$	×	×	×
$\|\Delta\eta(V, bb)\|$			×
H_{T}	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_{T}^{W}		×	
$m_{\ell\ell}$			×
$MV1c(b_1)$	×	×	×
$MV1c(b_2)$	×	×	×
	Only in 3-jet events		
$p_{\mathrm{T}}^{\mathrm{jet}_3}$	×	×	×
m_{bbj}	×	×	×

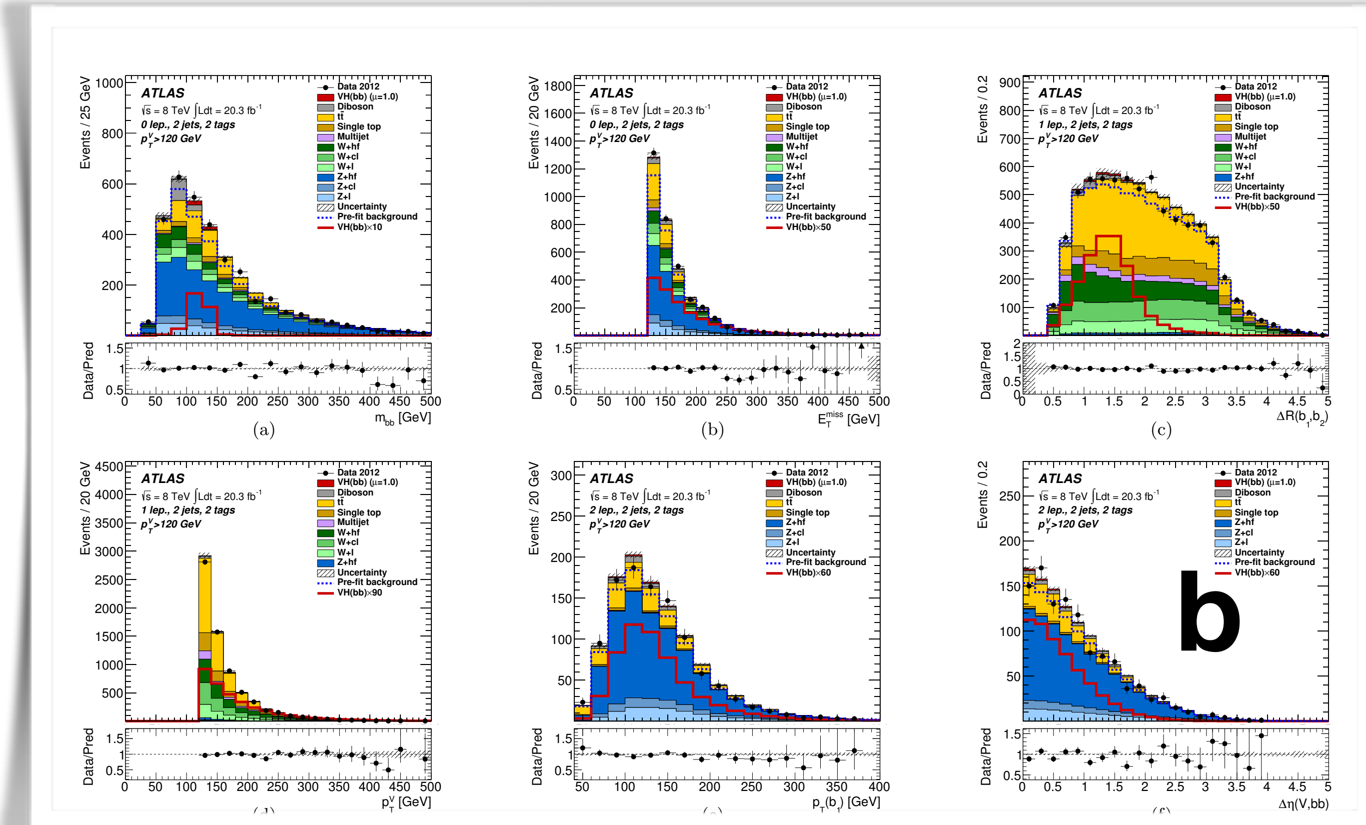
ττ Variables

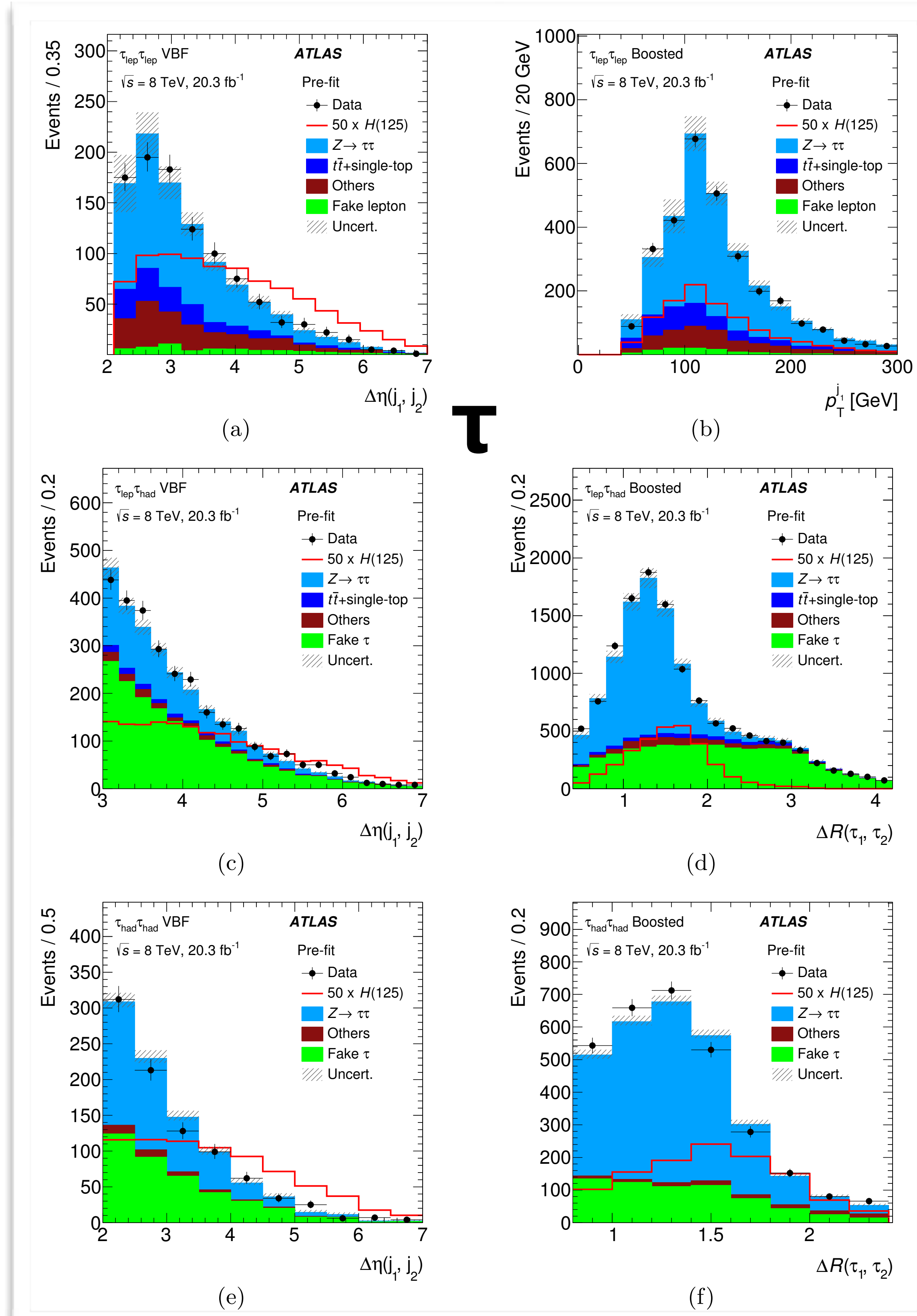
Variable	VBF			Boosted		
	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$
$m_{\tau\tau}^{\mathrm{MMC}}$	●	●	●	●	●	●
$\Delta R(\tau_1, \tau_2)$	●	●	●		●	●
$\Delta\eta(j_1, j_2)$	●	●	●			
m_{j_1, j_2}	●	●	●			
$\eta_{j_1} \times \eta_{j_2}$		●	●			
$p_{\mathrm{T}}^{\mathrm{Total}}$		●	●			
Sum p_{T}					●	●
$p_{\mathrm{T}}^{\tau_1}/p_{\mathrm{T}}^{\tau_2}$					●	●
$E_{\mathrm{T}}^{\mathrm{miss}}\phi$ centrality		●	●	●	●	●
m_{ℓ,ℓ,j_1}				●		
m_{ℓ_1,ℓ_2}				●		
$\Delta\phi(\ell_1, \ell_2)$				●		
Sphericity				●		
$p_{\mathrm{T}}^{\ell_1}$				●		
$p_{\mathrm{T}}^{j_1}$				●		
$E_{\mathrm{T}}^{\mathrm{miss}}/p_{\mathrm{T}}^{\ell_2}$				●		
m_{T}		●			●	
$\min(\Delta\eta_{\ell_1\ell_2,\mathrm{jets}})$	●					
$C_{\eta_1,\eta_2}(\eta_{\ell_1}) \cdot C_{\eta_1,\eta_2}(\eta_{\ell_2})$	●					
$C_{\eta_1,\eta_2}(\eta_{\ell})$		●				
$C_{\eta_1,\eta_2}(\eta_{j_3})$	●					
$C_{\eta_1,\eta_2}(\eta_{\tau_1})$			●			
$C_{\eta_1,\eta_2}(\eta_{\tau_2})$			●			

energy (p_{T}, MET, H_{T}) angular (ΔR,$\Delta\phi$) tagging

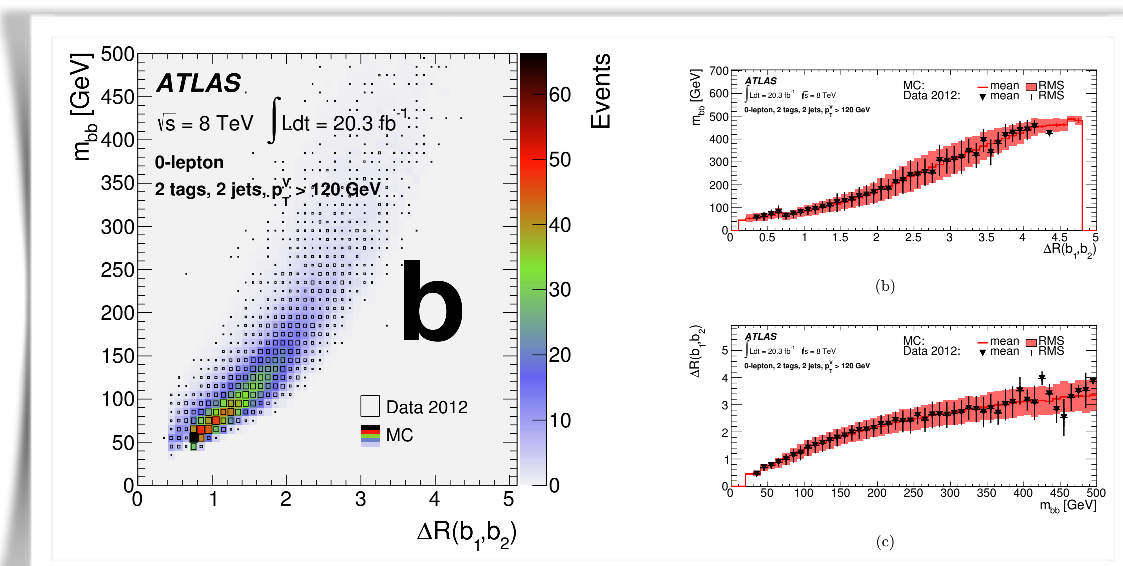
BDT Variables

Good modelling of variables





… and correlations



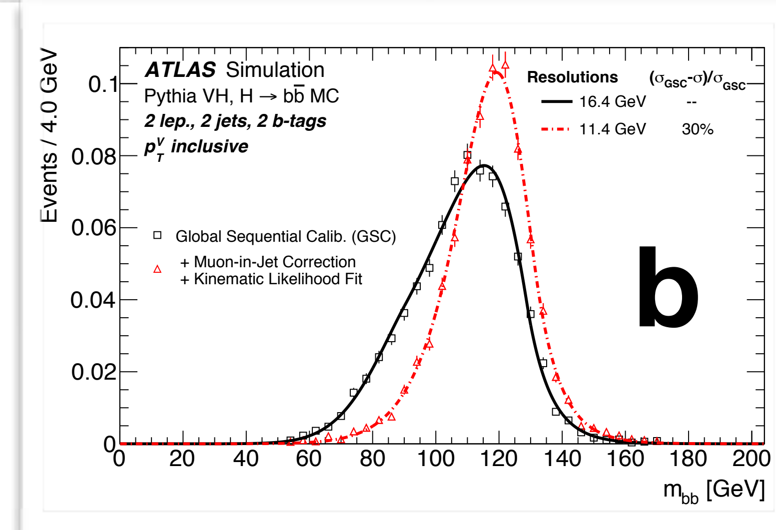
Mass Resolution

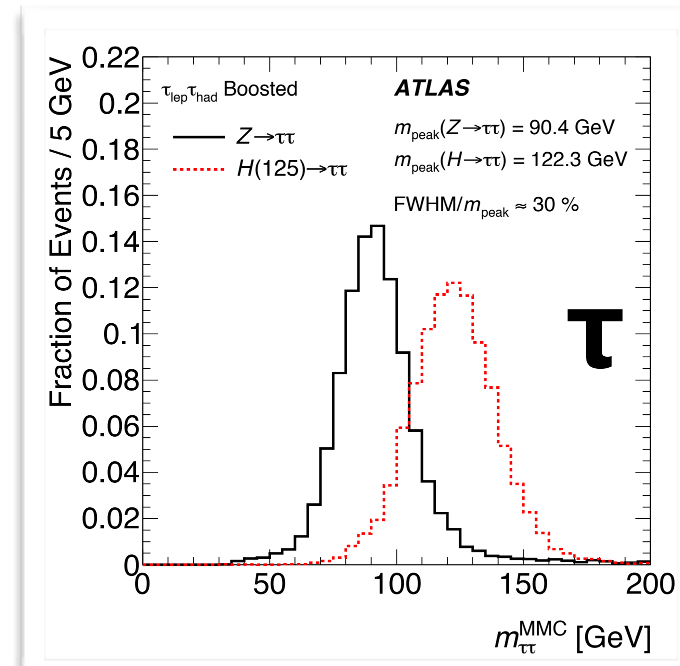
- σ: 2.3 GeV (μ), 11 GeV (b), ~19 GeV (τ)
- Improving reconstructed mass resolution improves sensitivity

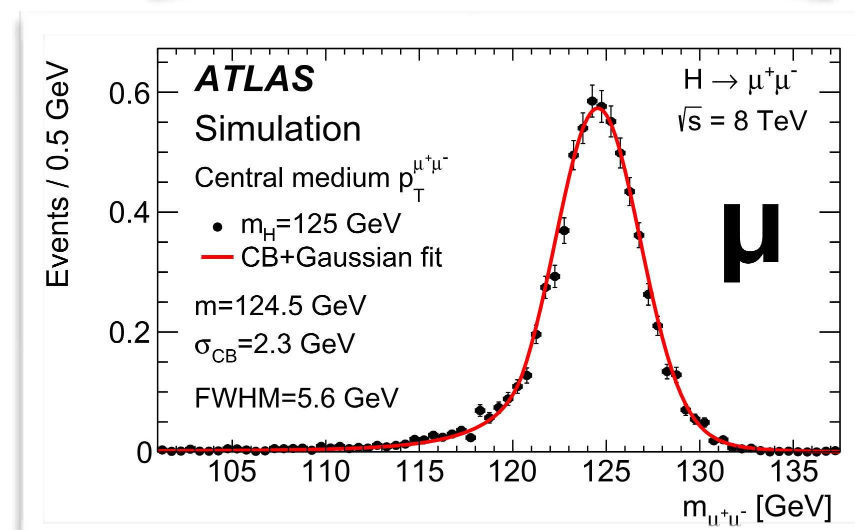

- b-jets: hadronic jet resolution
  - energy from muons from semi-leptonic decays
  - kinematic fit

+30%

- τ: resolution lost due to neutrinos
  - Leptonic: dominated by two neutrinos, but otherwise clean
  - Hadronic: calorimeter clusters
- Missing MMC calculator to solve for under constrained neutrino momenta

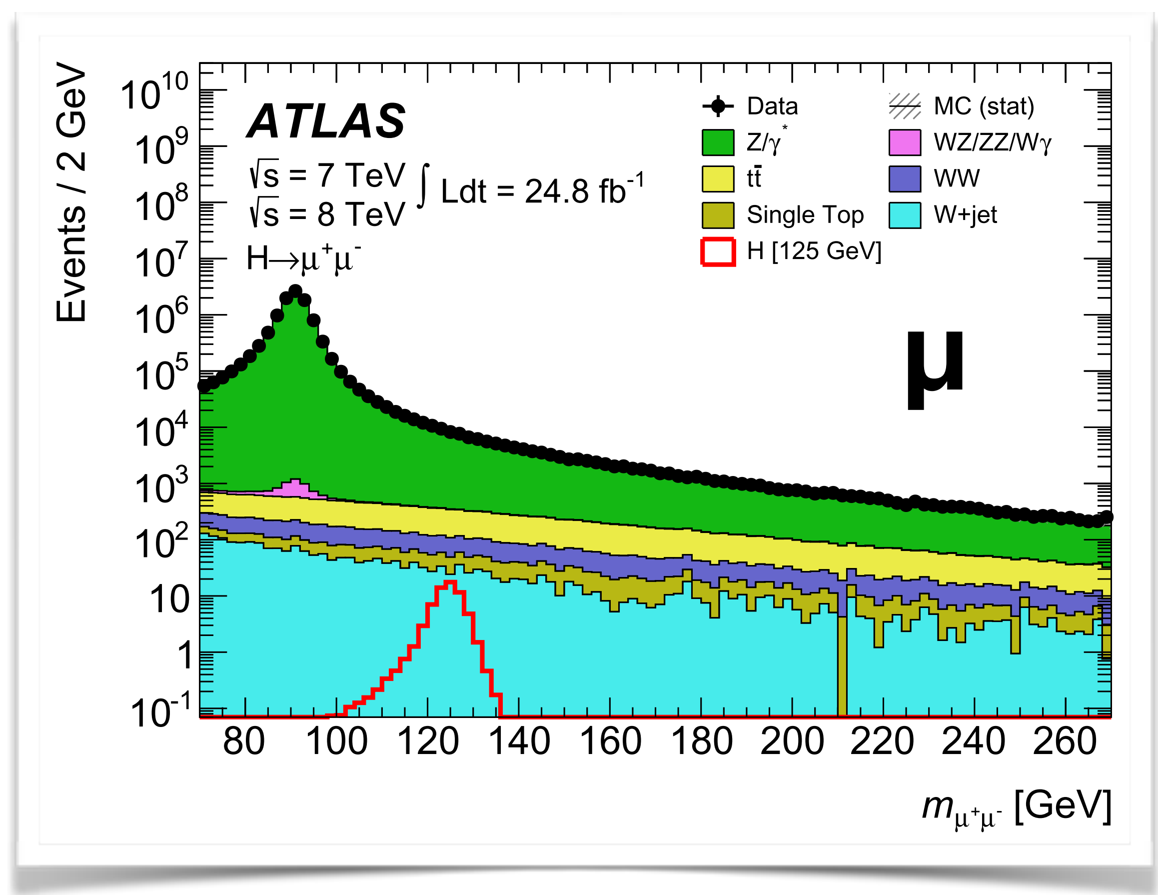






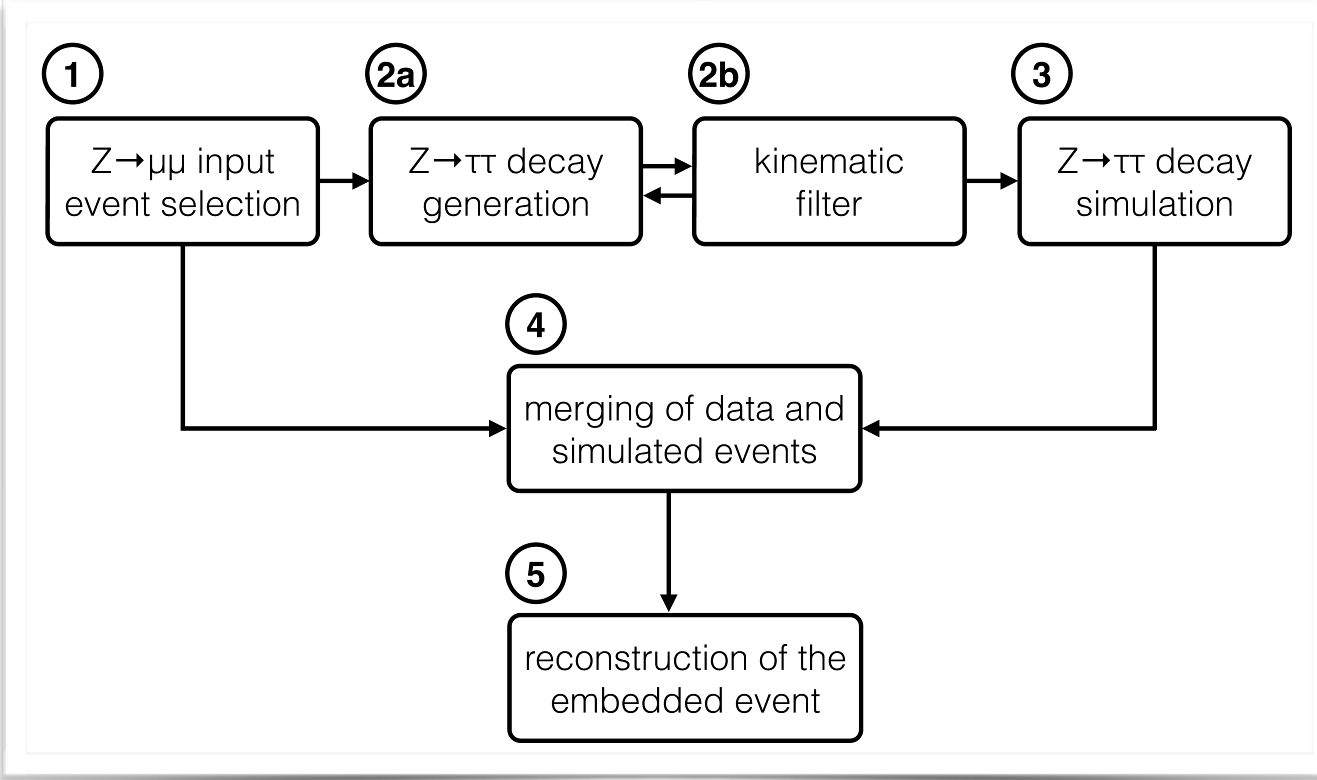
Backgrounds

- Similar problem:all three analyses have a difficult irreducible background from events with identical final state but with the Z-boson instead of the Higgs
  - Dominant background for μμ
- Different strategies to control backgrounds adopted in each analysis
  - MC-based partially constrained by data
  - Extracted from data with embedding
- bb: also backgrounds from V+jets and top
- Jet faking lepton backgrounds are extracted from data as typically poorly modelled in MC
  - Important both for 1-lepton bb and lep-had and had-had ττ

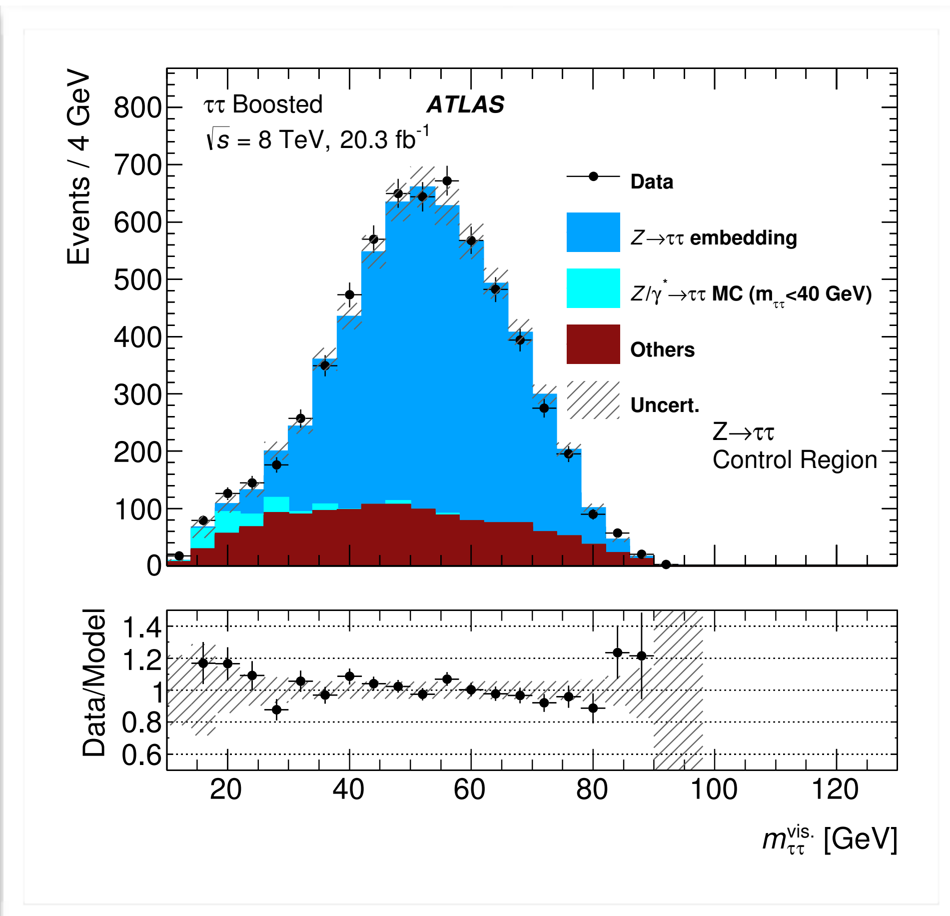


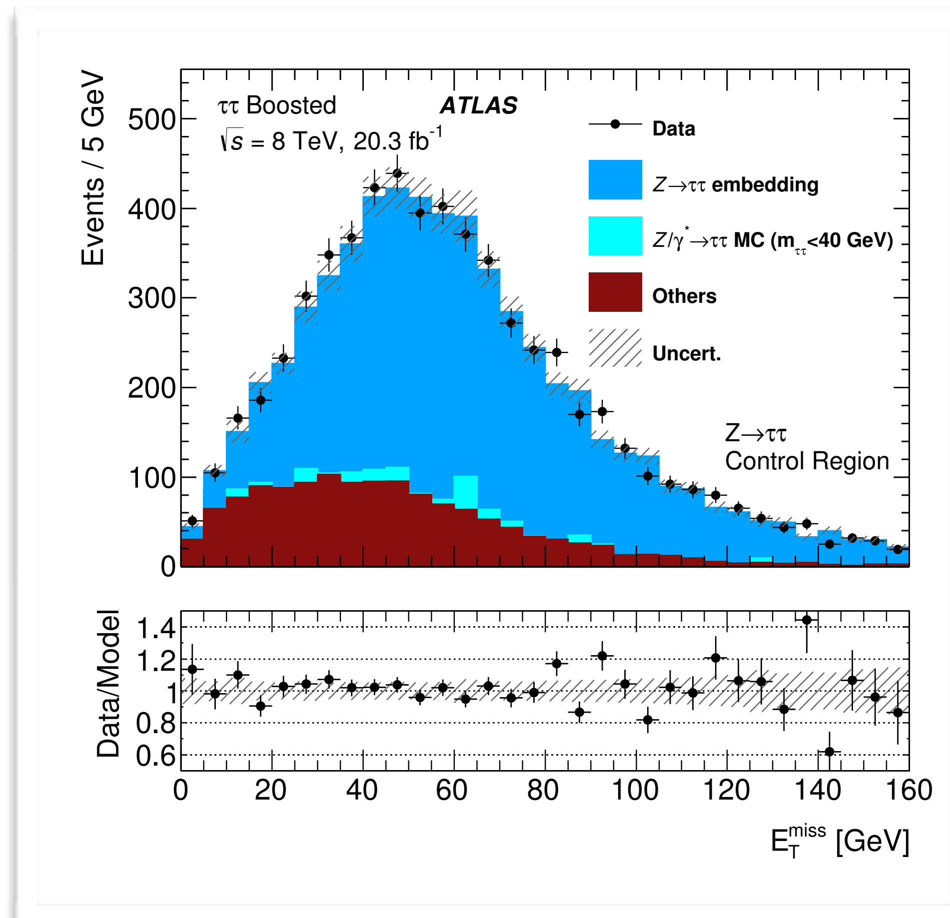
Embedding: controlling the Z→ττ background

Precisely estimate the Z→ττ background from data via embedding



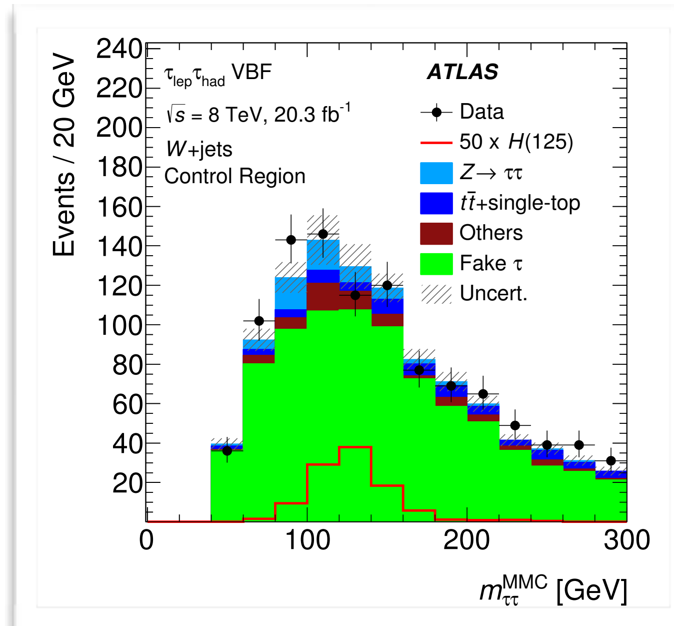
More details in Jessica Liebal's talk on Wednesday afternoon

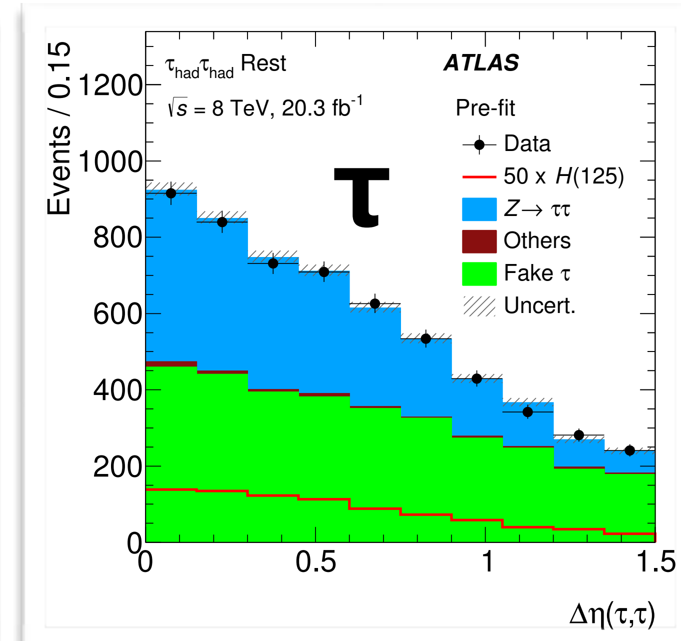


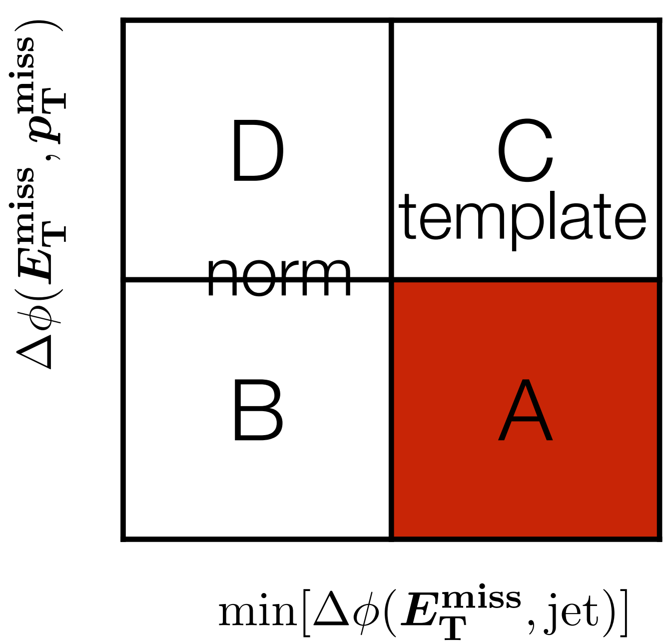


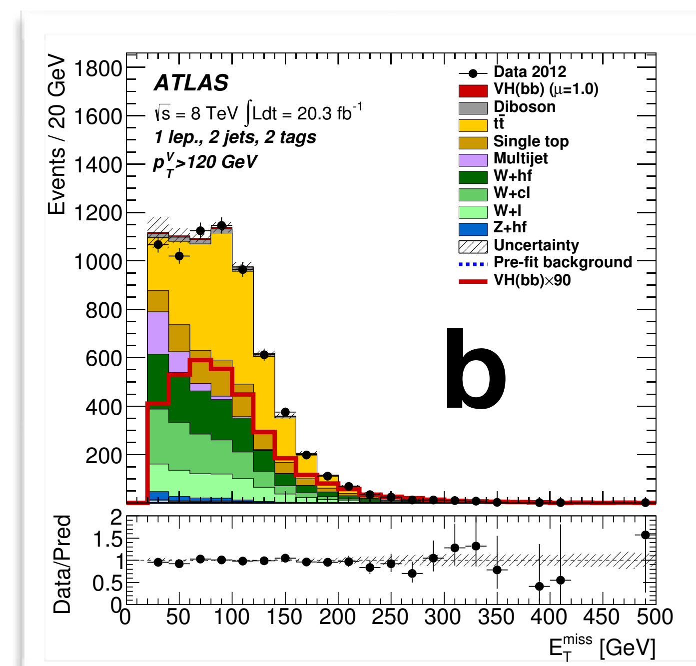
Multijet estimates

- **lep-had**: fake factor method
  - Medium/Loose not Medium
  - f(p_T, q/g, 1/3-track)
  - W+jets validation region
- **had-had**: template fit
  - Reverse isolation and require same-sign charge/other track multiplicity
  - Fit $\Delta\eta(\tau_{had}\tau_{had})$
- **0-lepton**: ABCD method
- **1-lepton**: template fit
  - Loosen isolation and tag and reweight
  - Fit E_T^{miss}



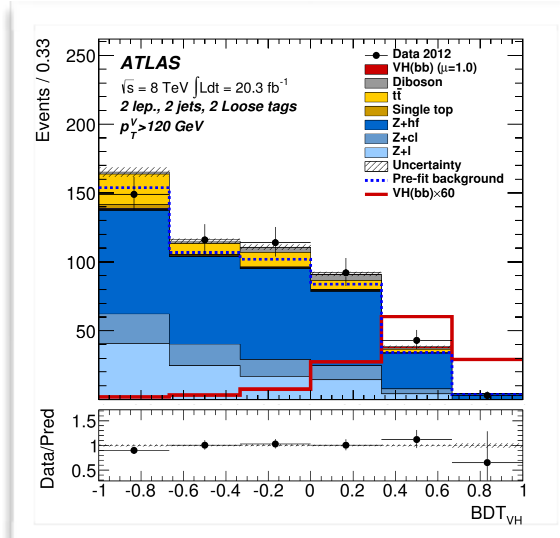


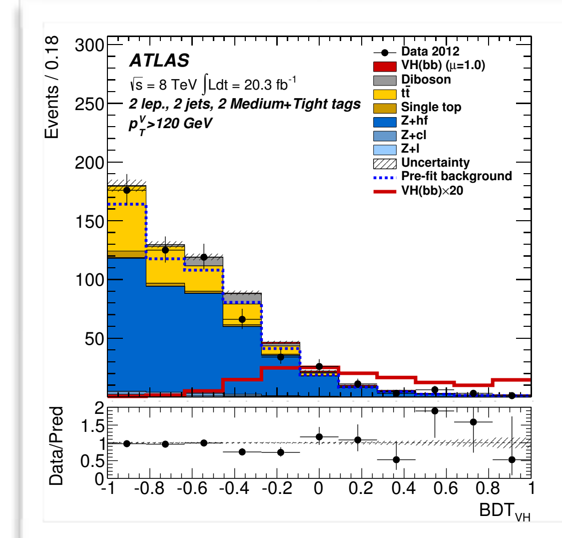


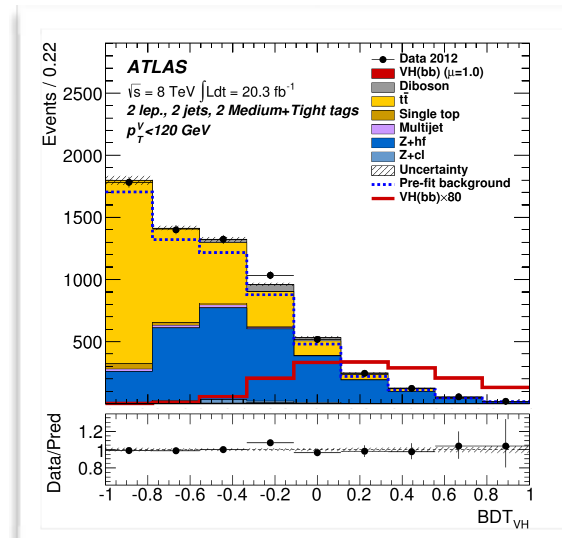


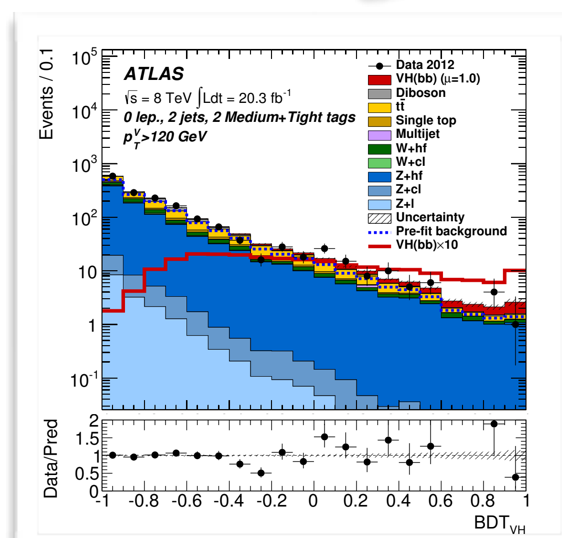
bb Backgrounds

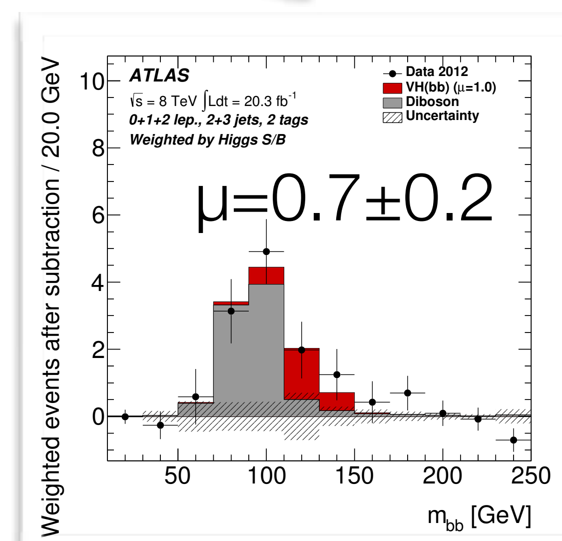
- bb: ~30% stat, ~25% syst
  - Systematics on backgrounds are already starting to play a key role in the analysis
- Many techniques used to estimate and validate backgrounds
  - Categories with different tightness of **tagging** requirements to control the **V +jets** backgrounds
  - **Cross channel fit** to use 1-lepton and 2-lepton channels to constrain backgrounds in 0-lepton
  - Cross-check by extracting the **diboson signal**











Systematic Uncertainties

τ

Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	$^{+0.27}_{-0.26}$
Jet energy scale	$\pm$ 0.13
Tau energy scale	$\pm$ 0.07
Tau identification	$\pm$ 0.06
Background normalisation	$\pm$ 0.12
Background estimate stat.	$\pm$ 0.10
BR ($H \to \tau\tau$)	$\pm$ 0.08
Parton shower/Underlying event	$\pm$ 0.04
PDF	$\pm$ 0.03
Total sys.	$^{+0.33}_{-0.26}$
Total	$^{+0.43}_{-0.37}$

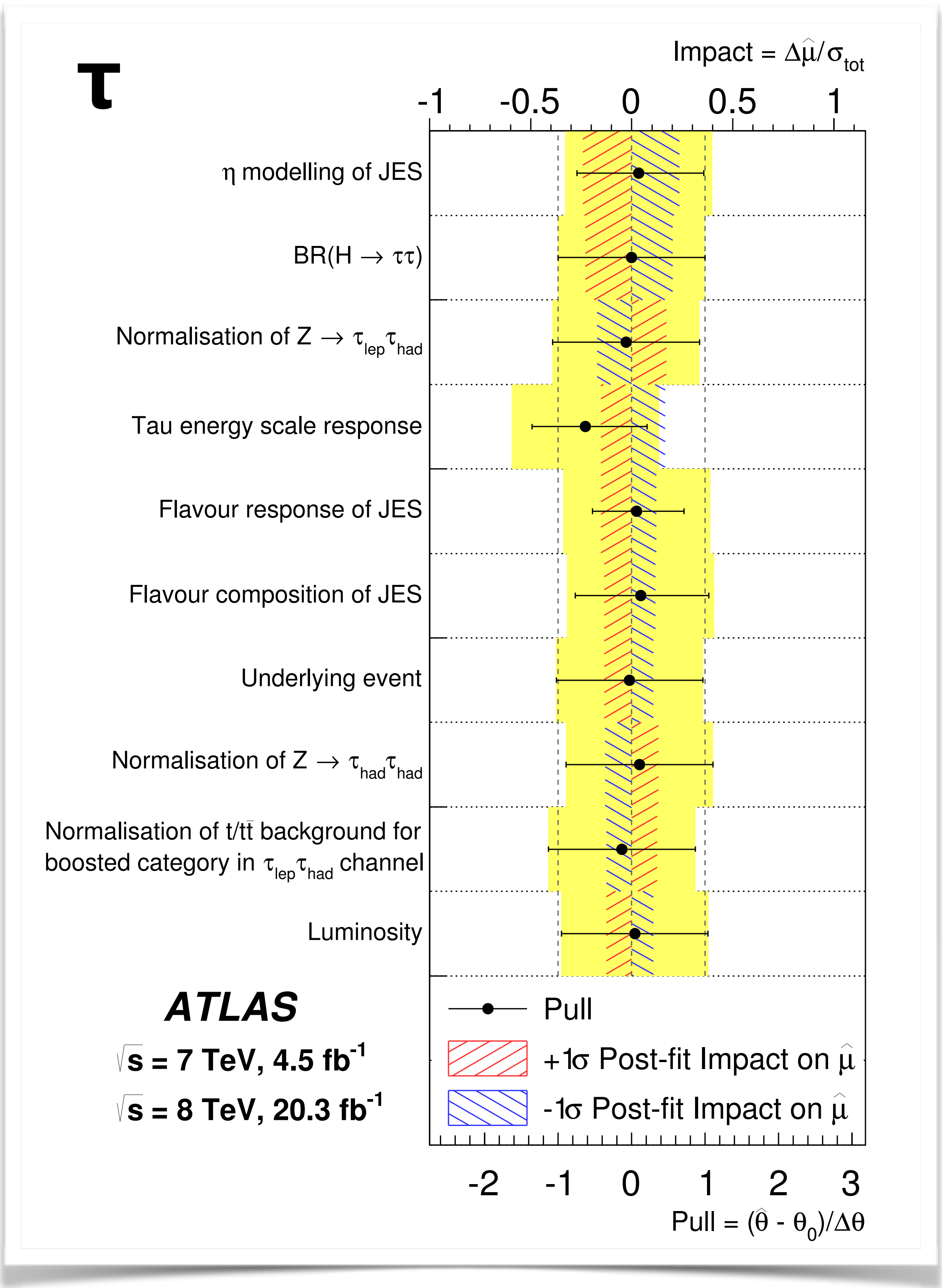
μ

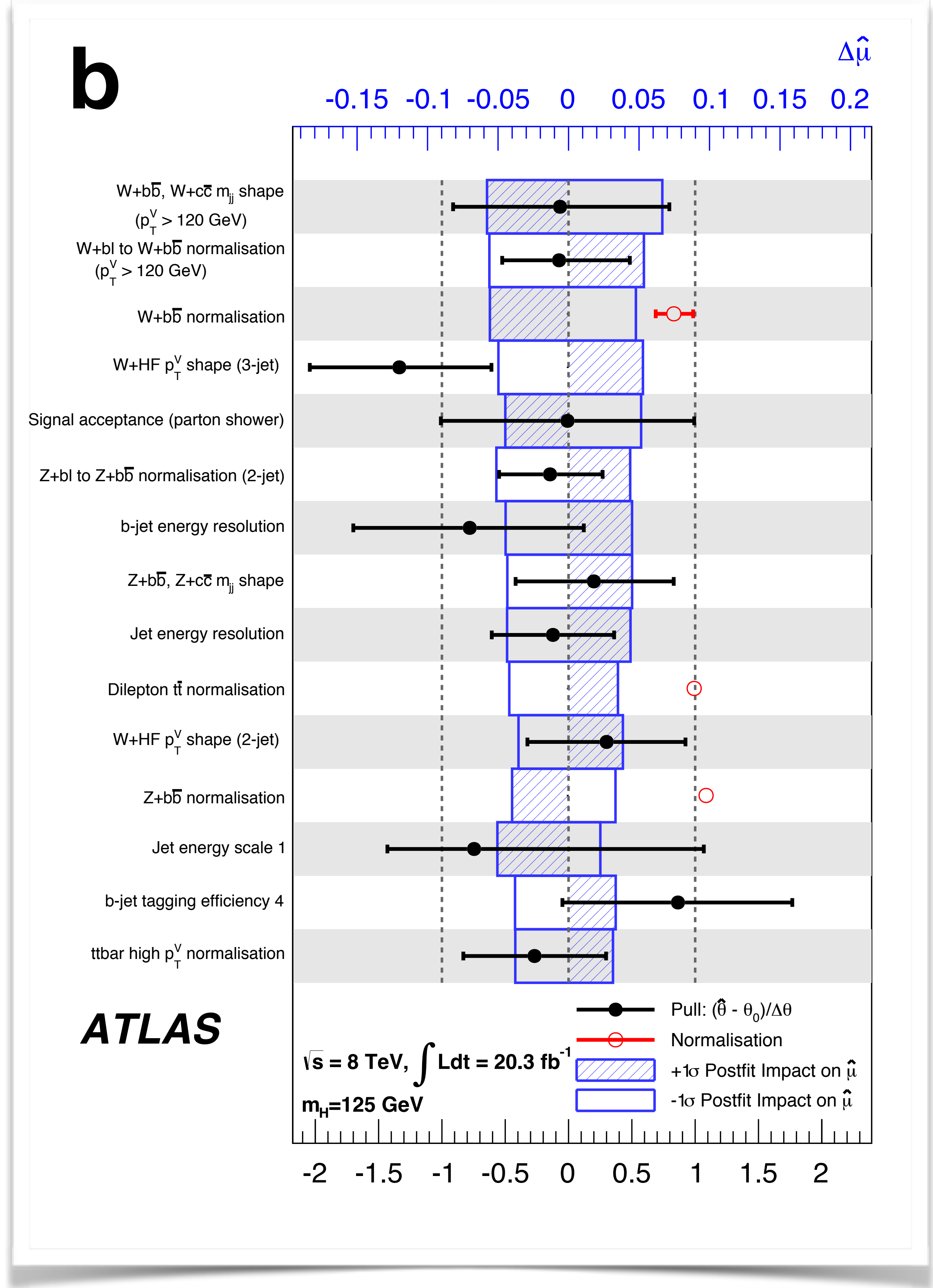
Source (experimental)	Uncertainty (%)
Luminosity	$\pm$1.8 (7 TeV), $\pm$2.8 (8 TeV)
Muon efficiency	$\pm$1
Muon momentum res.	$\pm$1
Muon trigger	$\pm$1.5
Muon isolation	$\pm$1.1
Pile-up reweighting	$\pm$1
Jet energy scale	$^{+3.4}_{-4.5}$ (VBF)
Source (theory)	**Uncertainty (%)**
Higgs boson branching ratio	$\pm$7
QCD scale	$\pm$8 (ggF), $\pm$1 (VBF, VH)
PDFs + α_s	$\pm$8 (ggF), $\pm$4 (VBF, VH)
ggF uncert. in VBF	$\pm$22
Multi-parton inter. in VBF	$\pm$9 (ggF), $\pm$4 (VBF)

b

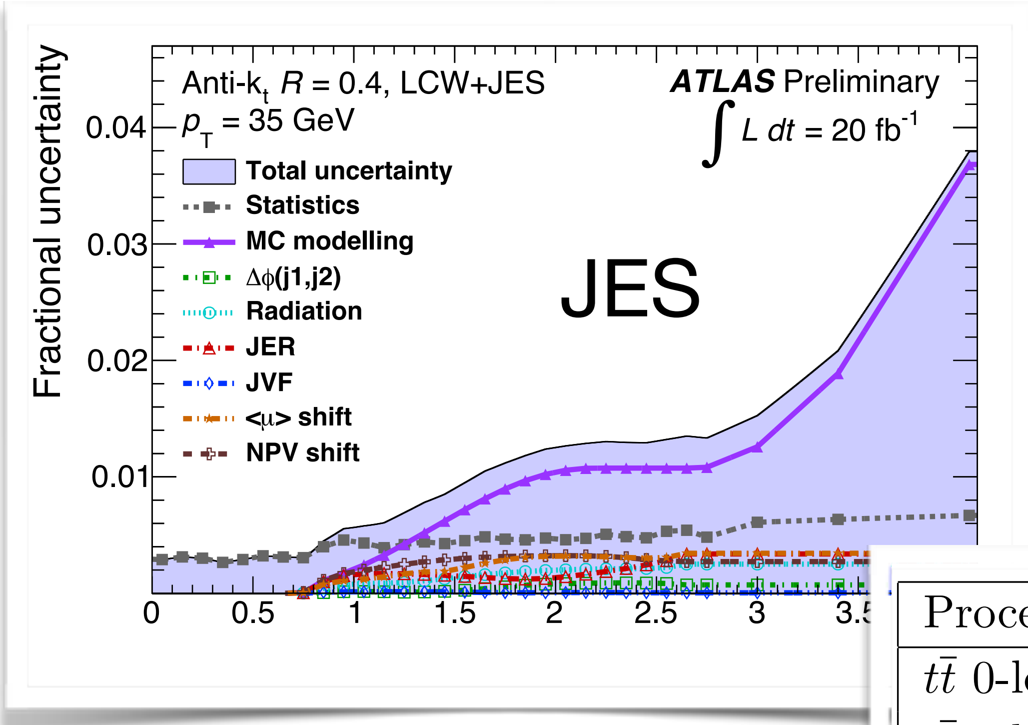
Signal	
Cross section (scale)	1% ($q\bar{q}$), 50% (gg)
Cross section (PDF)	2.4% ($q\bar{q}$), 17% (gg)
Branching ratio	3.3 %
Acceptance (scale)	1.5%–3.3%
3-jet acceptance (scale)	3.3%–4.2%
p_T^V shape (scale)	S
Acceptance (PDF)	2%–5%
p_T^V shape (NLO EW correction)	S
Acceptance (parton shower)	8%–13%
Z+jets	
Zl normalisation, 3/2-jet ratio	5%
Zcl 3/2-jet ratio	26%
Z+hf 3/2-jet ratio	20%
Z+hf/Zbb ratio	12%
$\Delta\phi(\text{jet}_1, \text{jet}_2)$, p_T^V, m_{bb}	S
W+jets	
Wl normalisation, 3/2-jet ratio	10%
Wcl, W+hf 3/2-jet ratio	10%
Wbl/Wbb ratio	35%
Wbc/Wbb, Wcc/Wbb ratio	12%
$\Delta\phi(\text{jet}_1, \text{jet}_2)$, p_T^V, m_{bb}	S
$t\bar{t}$	
3/2-jet ratio	20%
High/low-p_T^V ratio	7.5%
Top-quark p_T, m_{bb}, E_T^{miss}	S
Single top	
Cross section	4% (s-,t-channel), 7% (Wt)
Acceptance (generator)	3%–52%
m_{bb}, $p_T^{b_1}$	S
Diboson	
Cross section and acceptance (scale)	3%–29%
Cross section and acceptance (PDF)	2%–4%
m_{bb}	S
Multijet	
0-, 2-lepton channels normalisation	100%
1-lepton channel normalisation	2%–60%
Template variations, reweighting	S

Key systematics

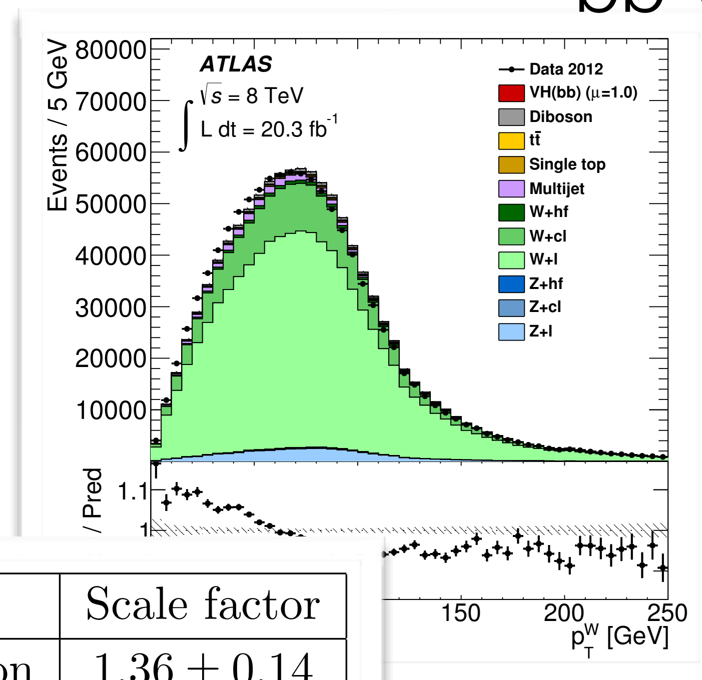


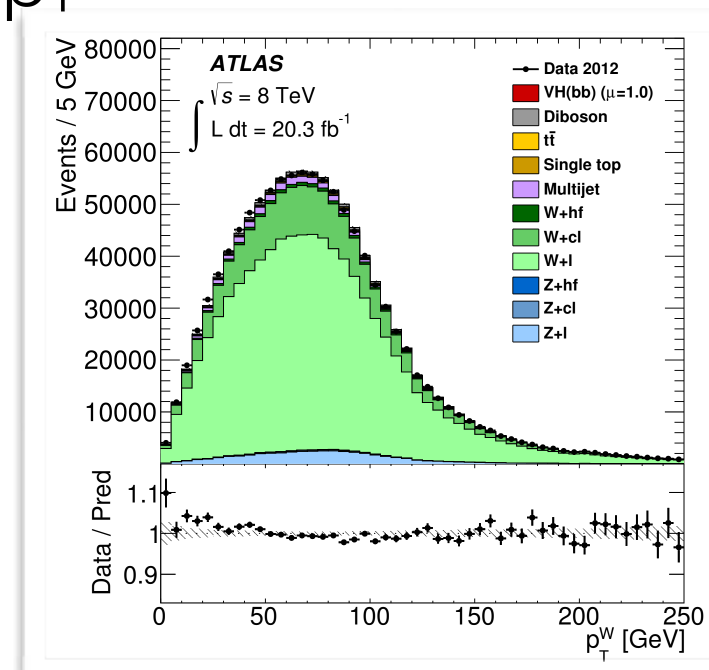


Systematics



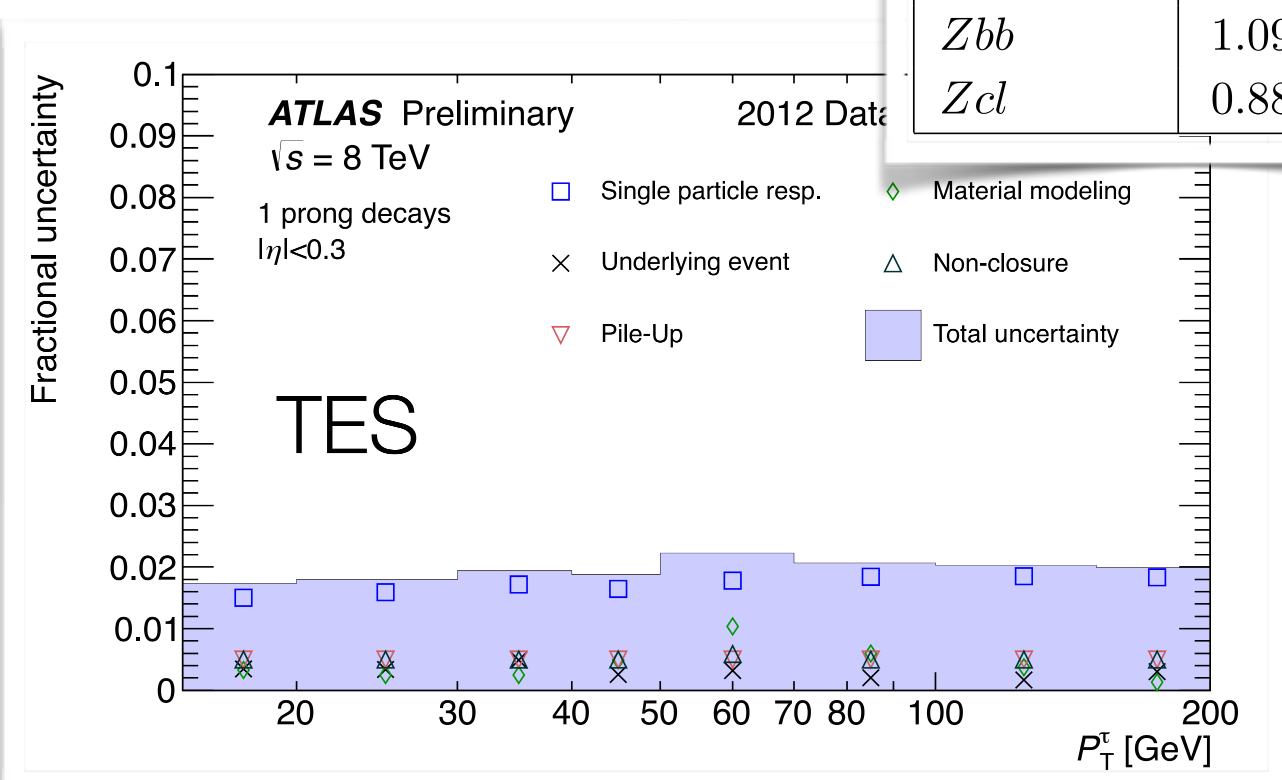
bb W pT

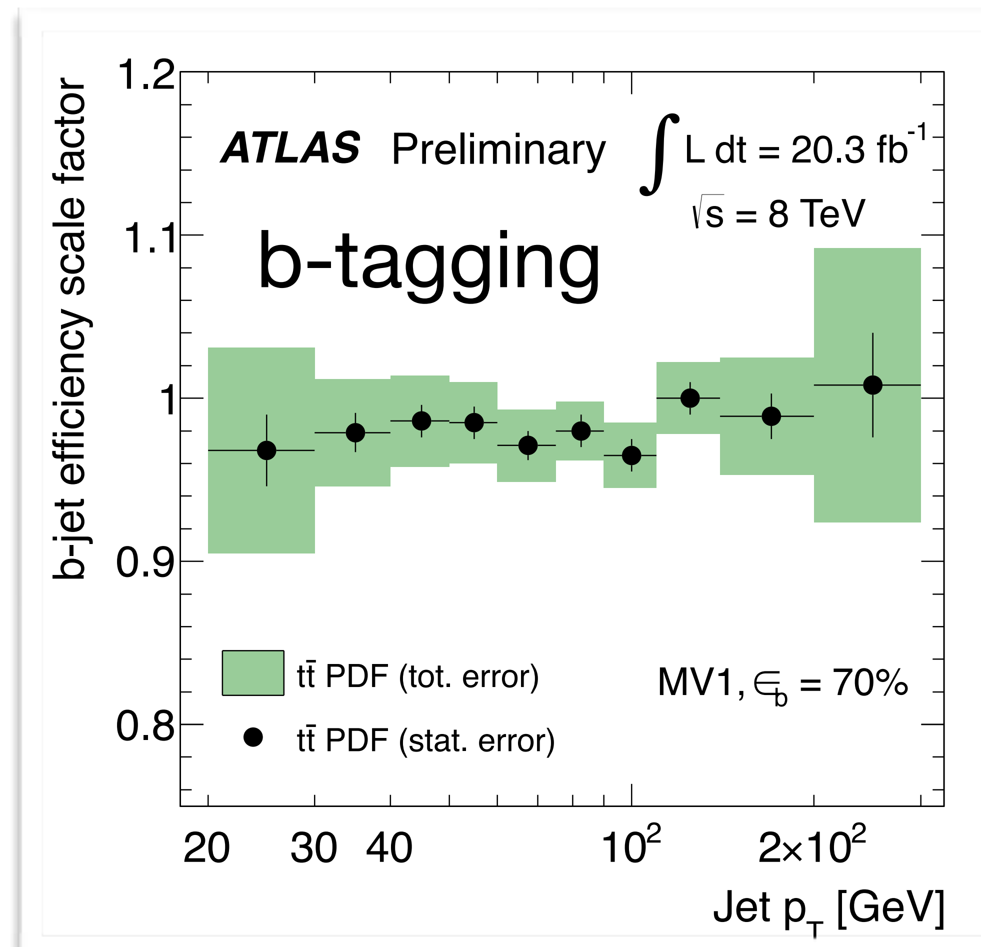




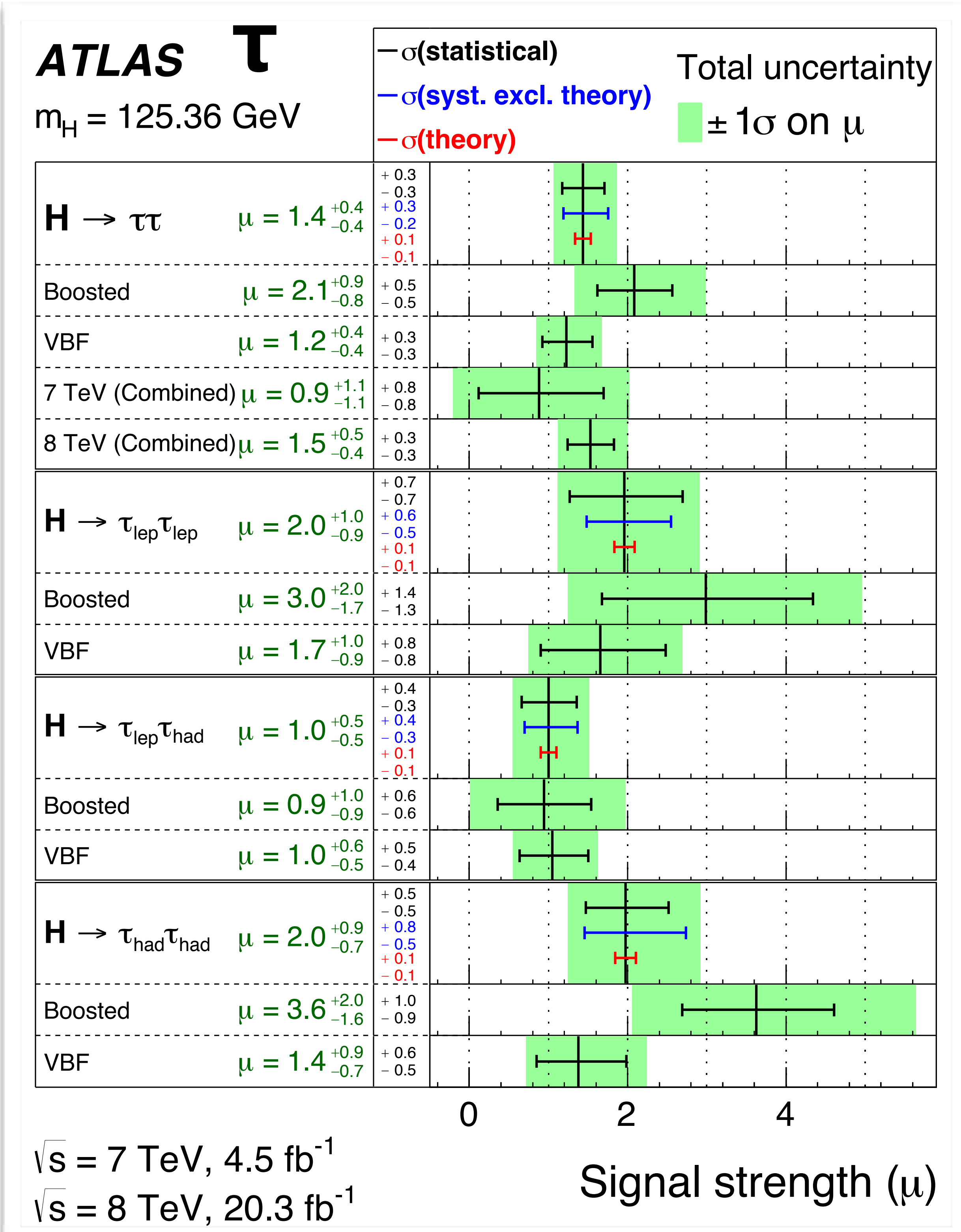
bb SF

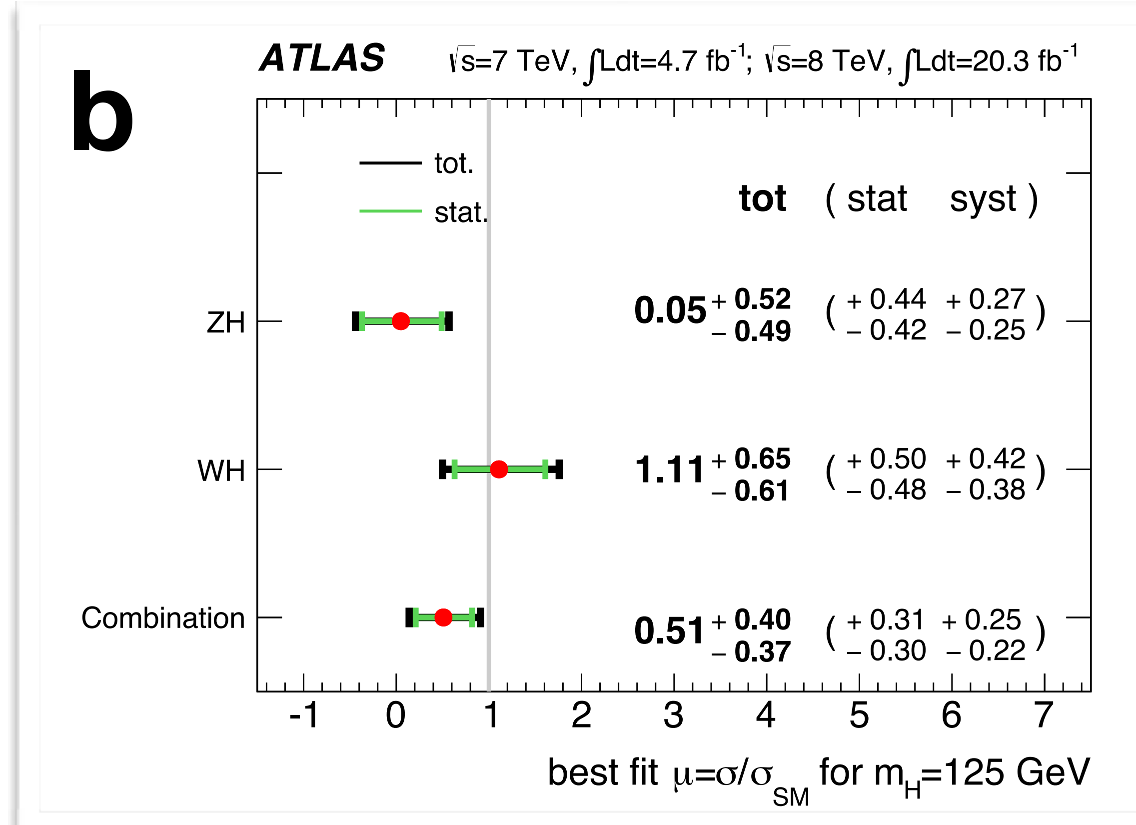
Process	Scale factor
$t\bar{t}$ 0-lepton	1.36 ± 0.14
$t\bar{t}$ 1-lepton	1.12 ± 0.09
$t\bar{t}$ 2-lepton	0.99 ± 0.04
Wbb	0.83 ± 0.15
Wcl	1.14 ± 0.10
Zbb	1.09 ± 0.05
Zcl	0.88 ± 0.12

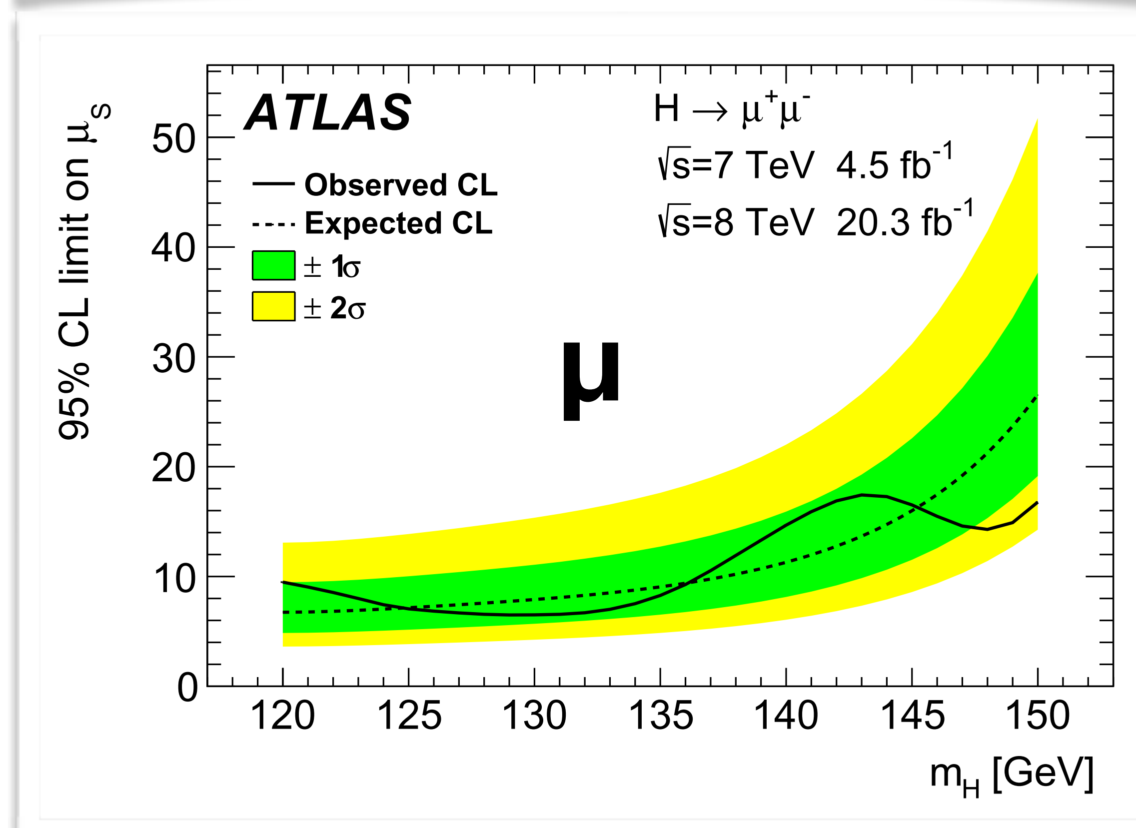




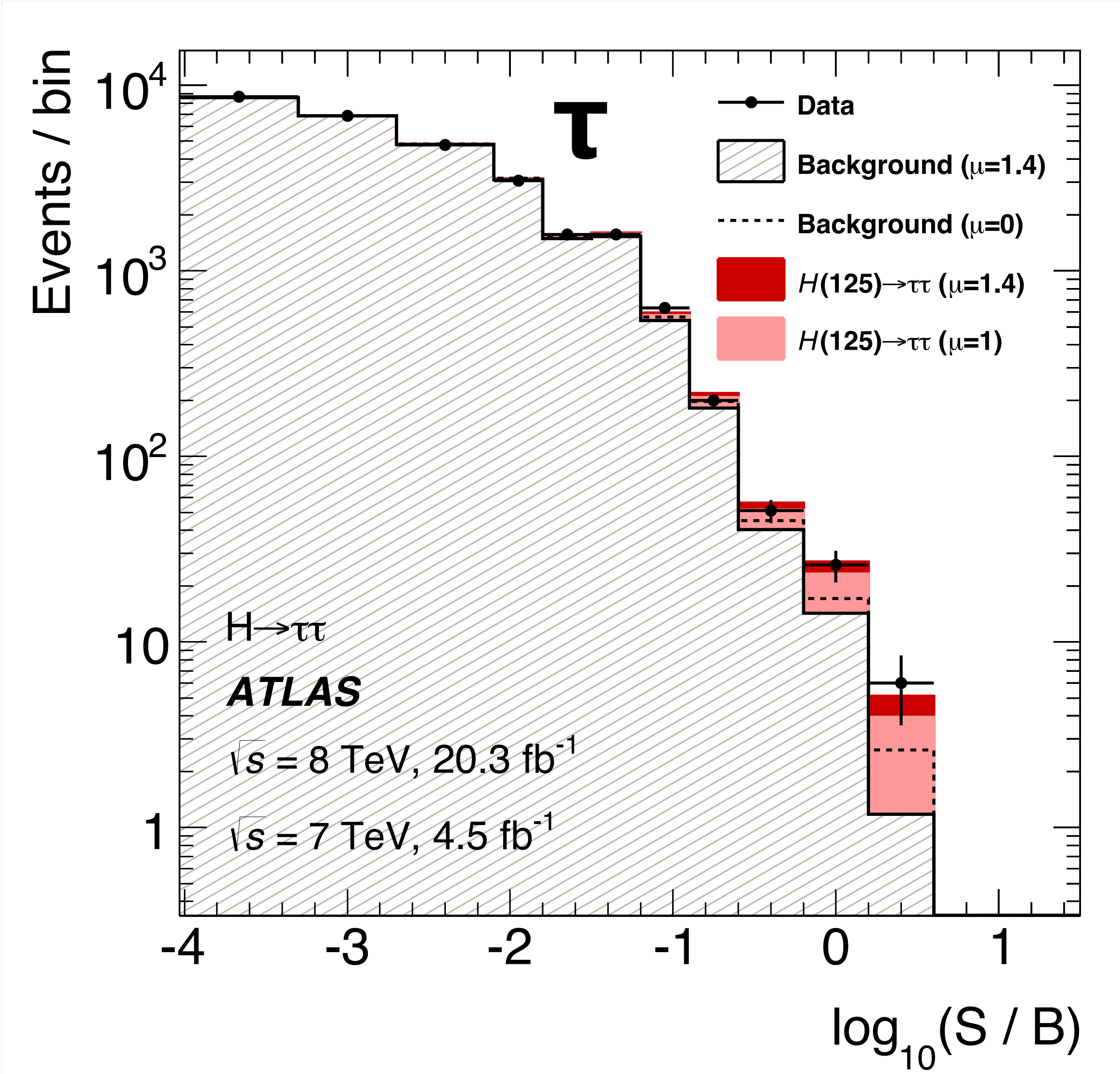
Results

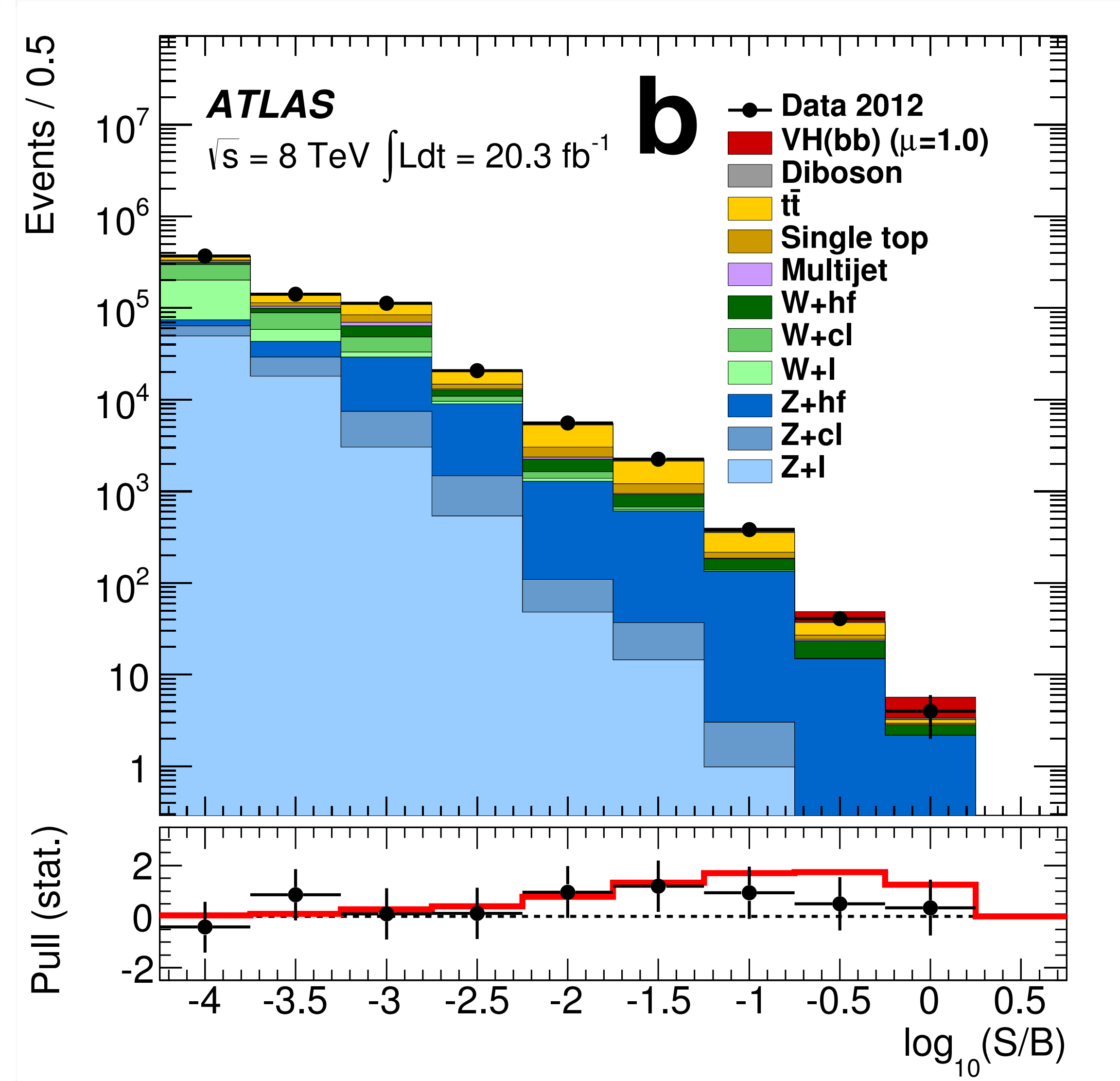

ATLAS
τ
m_H = 125.36 GeV
σ(statistical)
σ(syst. excl. theory)
σ(theory)
Total uncertainty
± 1σ on μ
H → ττ μ = 1.4 +0.4 −0.4
Boosted μ = 2.1 +0.9 −0.8
VBF μ = 1.2 +0.4 −0.4
7 TeV (Combined) μ = 0.9 +1.1 −1.1
8 TeV (Combined) μ = 1.5 +0.5 −0.4
H → τlepτlep μ = 2.0 +1.0 −0.9
Boosted μ = 3.0 +2.0 −1.7
VBF μ = 1.7 +1.0 −0.9
H → τlepτhad μ = 1.0 +0.5 −0.5
Boosted μ = 0.9 +1.0 −0.9
VBF μ = 1.0 +0.6 −0.5
H → τhadτhad μ = 2.0 +0.9 −0.7
Boosted μ = 3.6 +2.0 −1.6
VBF μ = 1.4 +0.9 −0.7
√s = 7 TeV, 4.5 fb-1
√s = 8 TeV, 20.3 fb-1
Signal strength (μ)


b
ATLAS √s=7 TeV, ∫Ldt=4.7 fb-1; √s=8 TeV, ∫Ldt=20.3 fb-1
tot.
stat.
tot (stat syst)
ZH 0.05 +0.52 −0.49 (+0.44 −0.42 +0.27 −0.25)
WH 1.11 +0.65 −0.61 (+0.50 −0.48 +0.42 −0.38)
Combination 0.51 +0.40 −0.37 (+0.31 −0.30 +0.25 −0.22)
best fit μ=σ/σSM for mH=125 GeV


ATLAS
H → μ+μ-
√s=7 TeV 4.5 fb-1
√s=8 TeV 20.3 fb-1
Observed CL
Expected CL
± 1σ
± 2σ
μ
95% CL limit on μS
mH [GeV]

Visualising the excess

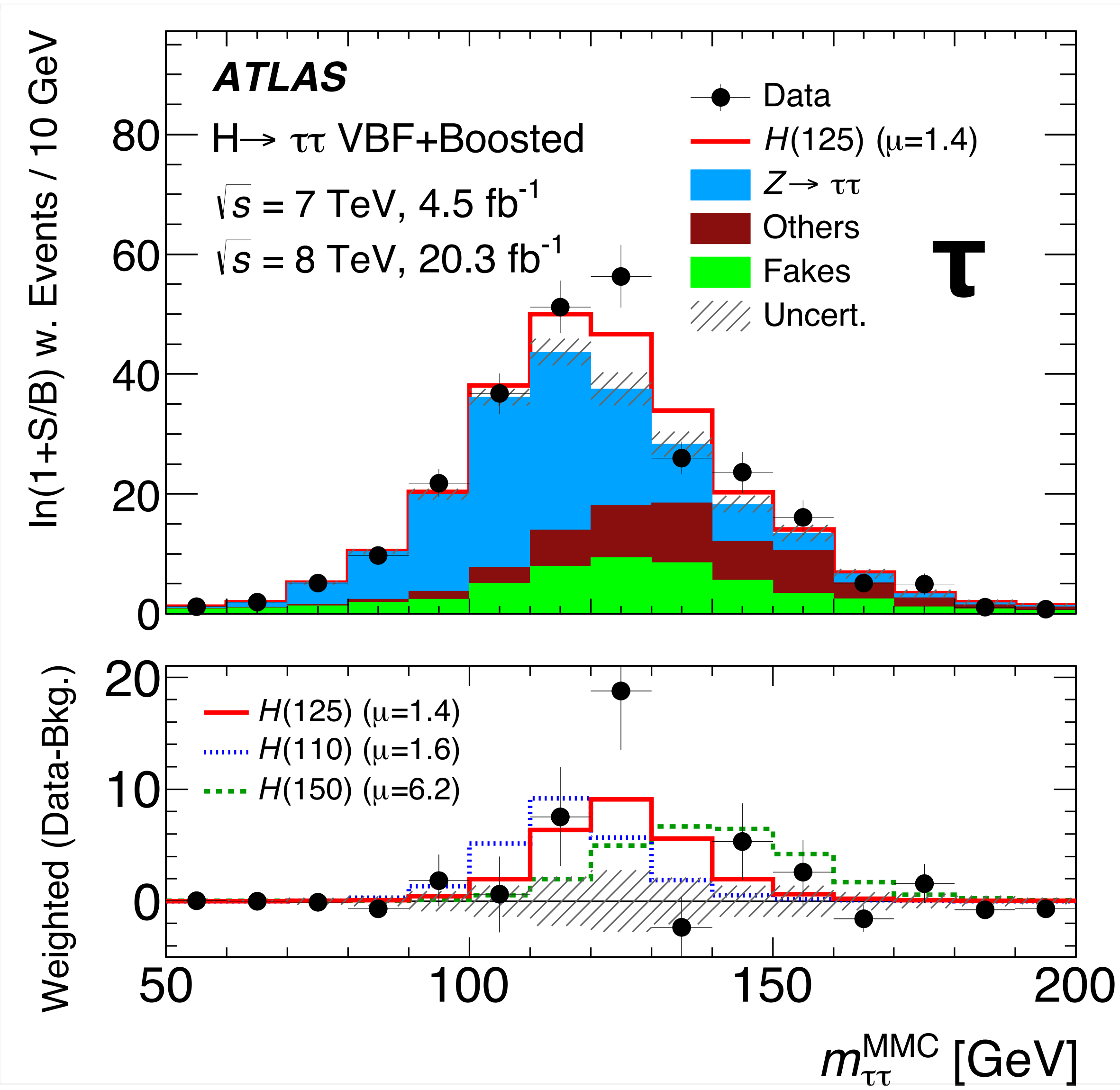


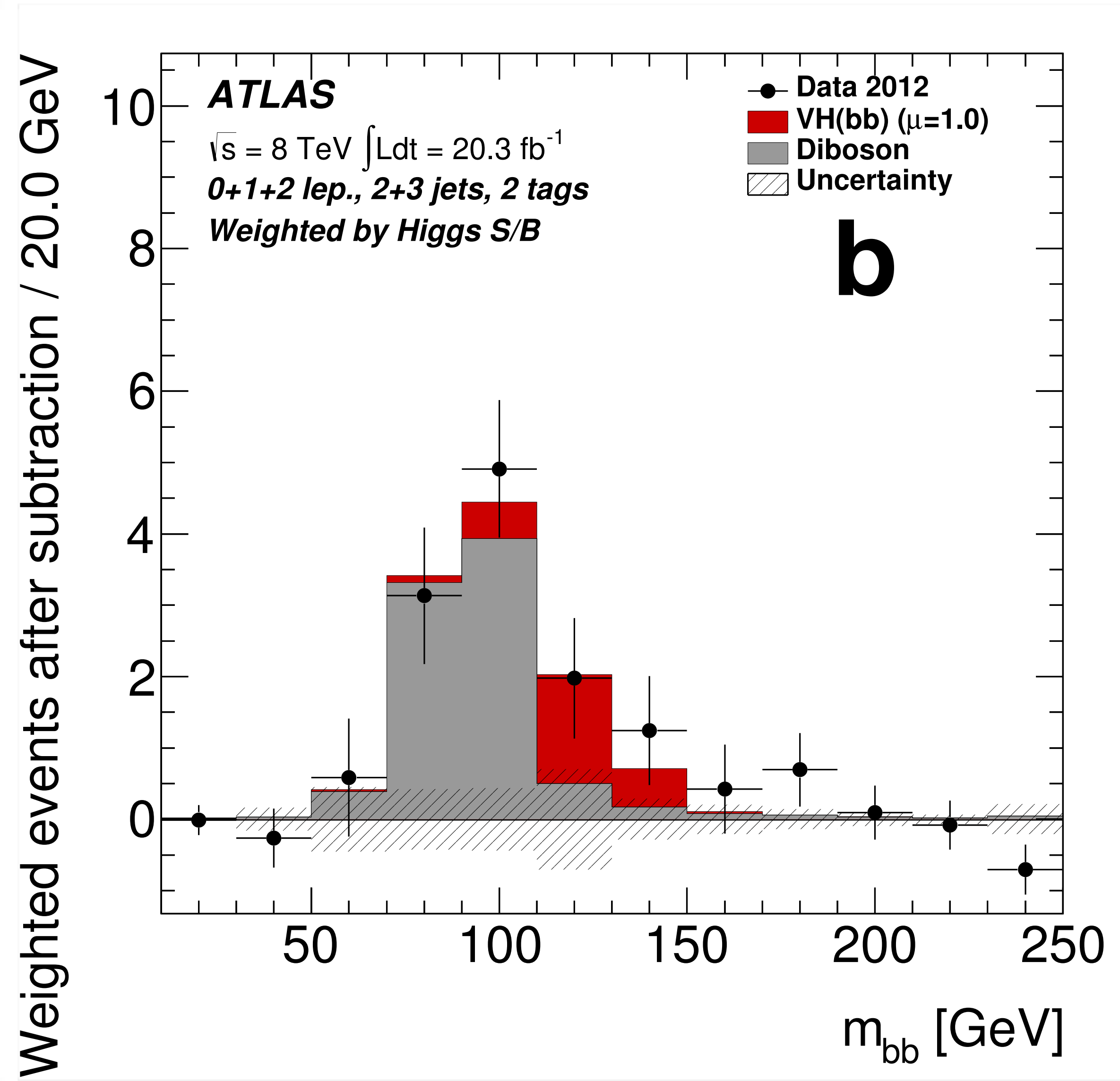


Order bins from all categories by expected S/B to visualise signal in a single plot

Warning: A number of possible definitions for the x-axis

Visualising the excess





Or project back onto mass variables for more physical visualisation

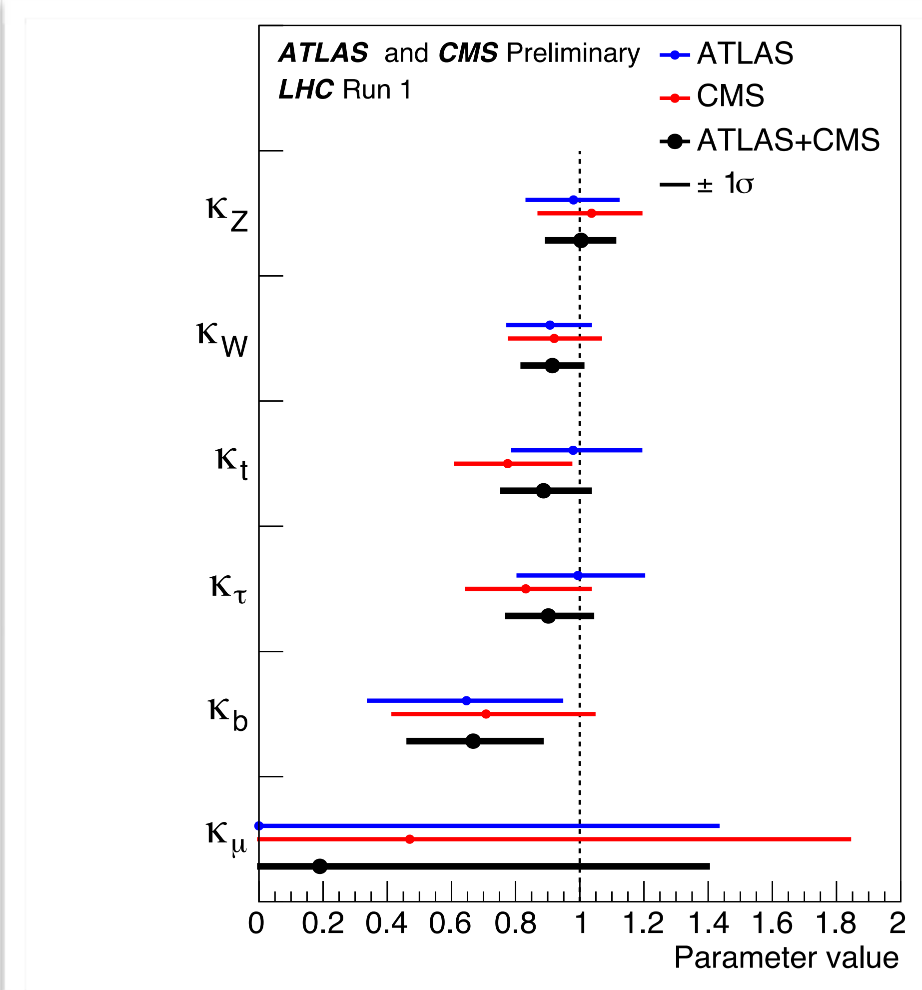
Note: need to weight events by 'significance', otherwise dominated by high statistics, low sensitivity regions

Excess is visible, though not yet sufficient statistics to see shape

Conclusion

- Higgs fermionic sector is a challenging and interesting area of active research
- ATLAS Run-1 combination
  - **4.4σ** (3.3σ exp) evidence for **τ** coupling
    - >5σ in combination with CMS
    - Large part of VBF observation
  - **1.7σ** (2.7σ exp) for **b** coupling
  - **7.0** (7.7 exp) x SM limit for **μ** coupling
- Run-1 has been an excellent proving ground in developing analyses in the fermionic channels
  - Higher statistics of Run-2 will only make them even more interesting

Parameter $\kappa_j \geq 0$	ATLAS+CMS Measured	ATLAS+CMS Expected uncertainty	ATLAS Measured	CMS Measured
κ_Z	$1.00^{+0.10}_{-0.11}$	$^{+0.10}_{-0.10}$	$0.98^{+0.14}_{-0.14}$	$1.04^{+0.15}_{-0.16}$
κ_W	$0.91^{+0.09}_{-0.09}$	$^{+0.09}_{-0.09}$	$0.91^{+0.12}_{-0.13}$	$0.92^{+0.14}_{-0.14}$
κ_t	$0.89^{+0.15}_{-0.13}$	$^{+0.14}_{-0.13}$	$0.98^{+0.21}_{-0.18}$	$0.78^{+0.20}_{-0.16}$
κ_τ	$0.90^{+0.14}_{-0.13}$	$^{+0.15}_{-0.14}$	$0.99^{+0.20}_{-0.18}$	$0.83^{+0.20}_{-0.18}$
κ_b	$0.67^{+0.22}_{-0.20}$	$^{+0.23}_{-0.22}$	$0.65^{+0.29}_{-0.30}$	$0.71^{+0.34}_{-0.29}$
κ_μ	$0.2^{+1.2}_{-0.2}$	$^{+0.9}_{-1.0}$	$0.0^{+1.4}$	$0.5^{+1.4}_{-0.5}$



References

- ττ: http://link.springer.com/article/10.1007/JHEP04(2015)117
    - Embedding: http://arxiv.org/abs/1506.05623
- bb: http://link.springer.com/article/10.1007/JHEP01(2015)069
    - (Tevatron: Phys.Rev.D 88, 052014 (2013))
- μμ: http://www.sciencedirect.com/science/article/pii/S0370269314006583
- ATLAS-CMS Coupling Combination: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-044/

Backup

μμ

Signal and Background Yields

Table 1
Number of expected signal events for $m_H = 125$ GeV, number of expected background events predicted by the MC simulation, and number of observed data events within a window of $|m_H - m_{\mu^+\mu^-}| \leq 2.5$ GeV after all selection criteria are applied. Only statistical uncertainties are given. The theoretical systematic uncertainty on the dominant Z/γ^* background is about 4%. The MC background yields are given to illustrate the expected background composition.

	7 TeV	8 TeV
Signal (125 GeV)	5.6 ± 0.1	32.7 ± 0.2
Z/γ^*	3110 ± 40	$16\,660 \pm 270$
$WZ/ZZ/W\gamma$	2.2 ± 0.2	12.3 ± 0.7
$t\bar{t}$	75.6 ± 1.8	509.2 ± 2.7
WW	23.2 ± 0.5	123.3 ± 1.6
Single top	7.2 ± 0.9	54.5 ± 0.6
W + jets	3.2 ± 1.5	38 ± 4
Total Bkg.	3220 ± 40	$17\,390 \pm 270$
Observed	3344	17 745

bb

bb Generators

Process	Generator
Signal$^{(\star)}$	
$q\bar{q} \to ZH \to \nu\nu bb/\ell\ell bb$	PYTHIA8
$gg \to ZH \to \nu\nu bb/\ell\ell bb$	POWHEG+PYTHIA8
$q\bar{q} \to WH \to \ell\nu bb$	PYTHIA8
Vector boson + jets	
$W \to \ell\nu$	SHERPA 1.4.1
$Z/\gamma* \to \ell\ell$	SHERPA 1.4.1
$Z \to \nu\nu$	SHERPA 1.4.1
Top-quark	
$t\bar{t}$	POWHEG+PYTHIA
t-channel	ACERMC+PYTHIA
s-channel	POWHEG+PYTHIA
Wt	POWHEG+PYTHIA
Diboson$^{(\star)}$	POWHEG+PYTHIA8
WW	POWHEG+PYTHIA8
WZ	POWHEG+PYTHIA8
ZZ	POWHEG+PYTHIA8

Table 1. The generators used for the simulation of the signal and background processes. ($\star$) For the analysis of the 7 TeV data, PYTHIA8 is used for the simulation of the $gg \to ZH$ process, and HERWIG for the simulation of diboson processes.

VH(bb) Selection Cuts

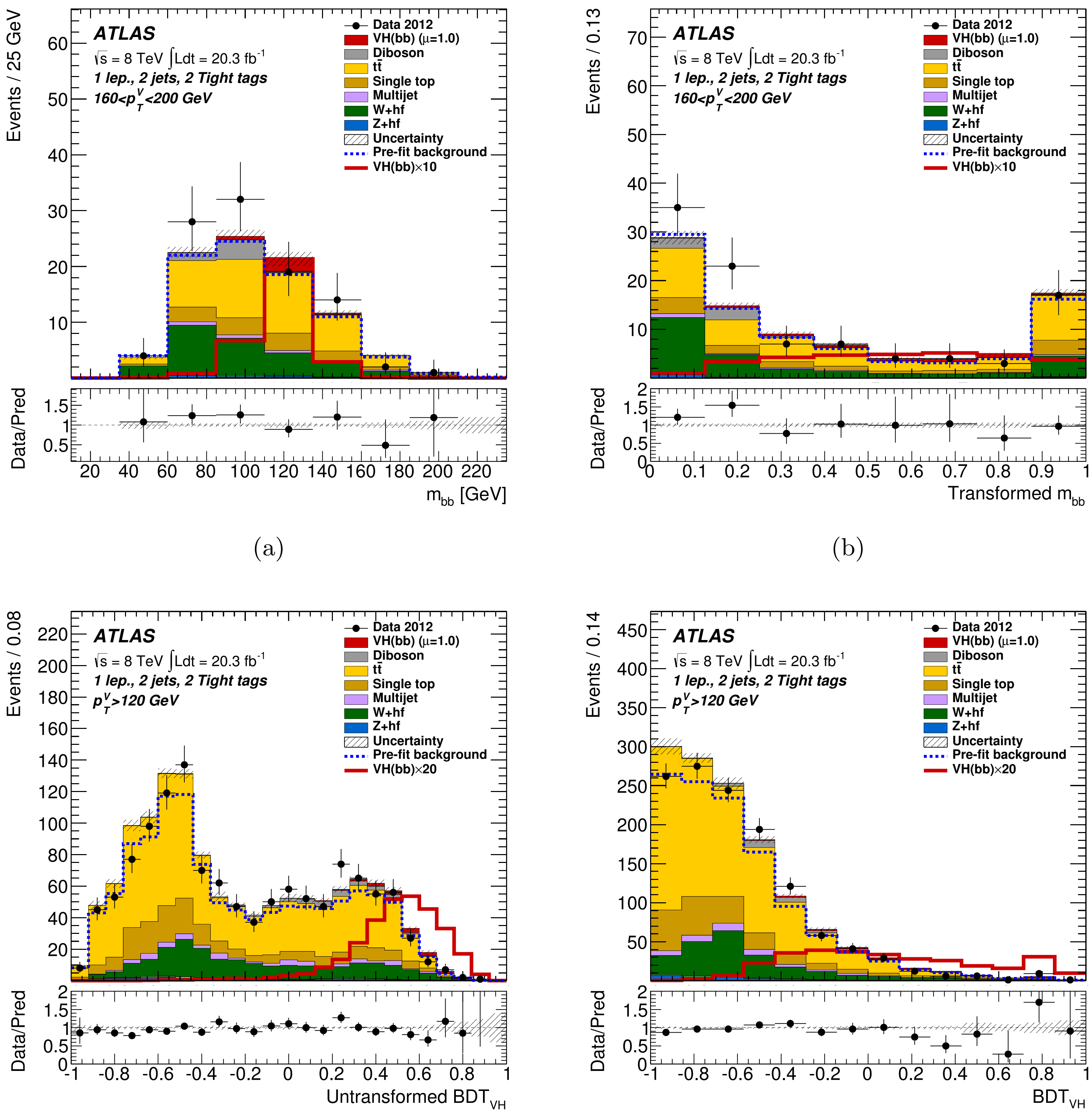
<table>
<tr><td>Variable</td><td colspan="5">Dijet-mass analysis</td><td colspan="2">Multivariate analysis</td></tr>
<tr><td colspan="8">Common selection</td></tr>
<tr><td>p_{T}^{V} [GeV]</td><td>0–90</td><td>$90^{(*)}$–120</td><td>120–160</td><td>160–200</td><td>> 200</td><td>0–120</td><td>> 120</td></tr>
<tr><td>$\Delta R(\mathrm{jet}_1, \mathrm{jet}_2)$</td><td>0.7–3.4</td><td>0.7–3.0</td><td>0.7–2.3</td><td>0.7–1.8</td><td>< 1.4</td><td colspan="2">> 0.7 (p_{T}^{V}<200 GeV)</td></tr>
<tr><td colspan="8">0-lepton selection</td></tr>
<tr><td>$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]</td><td rowspan="5">NU</td><td>> 30</td><td colspan="3">> 30</td><td rowspan="5">NU</td><td>> 30</td></tr>
<tr><td>$\Delta\phi(\boldsymbol{E}_{\mathbf{T}}^{\mathbf{miss}}, \boldsymbol{p}_{\mathbf{T}}^{\mathbf{miss}})$</td><td>$< \pi/2$</td><td colspan="3">$< \pi/2$</td><td>$< \pi/2$</td></tr>
<tr><td>$\min[\Delta\phi(\boldsymbol{E}_{\mathbf{T}}^{\mathbf{miss}}, \mathrm{jet})]$</td><td>–</td><td colspan="3">> 1.5</td><td>> 1.5</td></tr>
<tr><td>$\Delta\phi(\boldsymbol{E}_{\mathbf{T}}^{\mathbf{miss}}, \mathrm{dijet})$</td><td>$> 2.2$</td><td colspan="3">$> 2.8$</td><td>–</td></tr>
<tr><td>$\sum_{i=1}^{N_{\mathrm{jet}}=2(3)} p_{\mathrm{T}}^{\mathrm{jet}_i}$ [GeV]</td><td>> 120 (NU)</td><td colspan="3">> 120 (150)</td><td>> 120 (150)</td></tr>
<tr><td colspan="8">1-lepton selection</td></tr>
<tr><td>m_{T}^{W} [GeV]</td><td colspan="5">< 120</td><td colspan="2">–</td></tr>
<tr><td>H_{T} [GeV]</td><td colspan="2">> 180</td><td colspan="3">–</td><td>> 180</td><td>–</td></tr>
<tr><td>$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]</td><td colspan="2">–</td><td colspan="2">> 20</td><td>> 50</td><td>–</td><td>> 20</td></tr>
<tr><td colspan="8">2-lepton selection</td></tr>
<tr><td>$m_{\ell\ell}$ [GeV]</td><td colspan="5">83-99</td><td colspan="2">71-121</td></tr>
<tr><td>$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]</td><td colspan="5">< 60</td><td colspan="2">–</td></tr>
</table>

VH(bb) Acceptance

$m_H = 125\,\text{GeV}$ at $\sqrt{s} = 8\text{TeV}$				
Process	Cross section $\times$ BR [fb]	Acceptance [%]		
		0-lepton	1-lepton	2-lepton
$q\bar{q} \to (Z \to \ell\ell)(H \to b\bar{b})$	14.9	–	1.3 (1.1)	13.4 (10.9)
$gg \to (Z \to \ell\ell)(H \to b\bar{b})$	1.3	–	0.9 (0.7)	10.5 (8.1)
$q\bar{q} \to (W \to \ell\nu)(H \to b\bar{b})$	131.7	0.3 (0.3)	4.2 (3.7)	–
$q\bar{q} \to (Z \to \nu\nu)(H \to b\bar{b})$	44.2	4.0 (3.8)	–	–
$gg \to (Z \to \nu\nu)(H \to b\bar{b})$	3.8	5.5 (5.0)	–	–

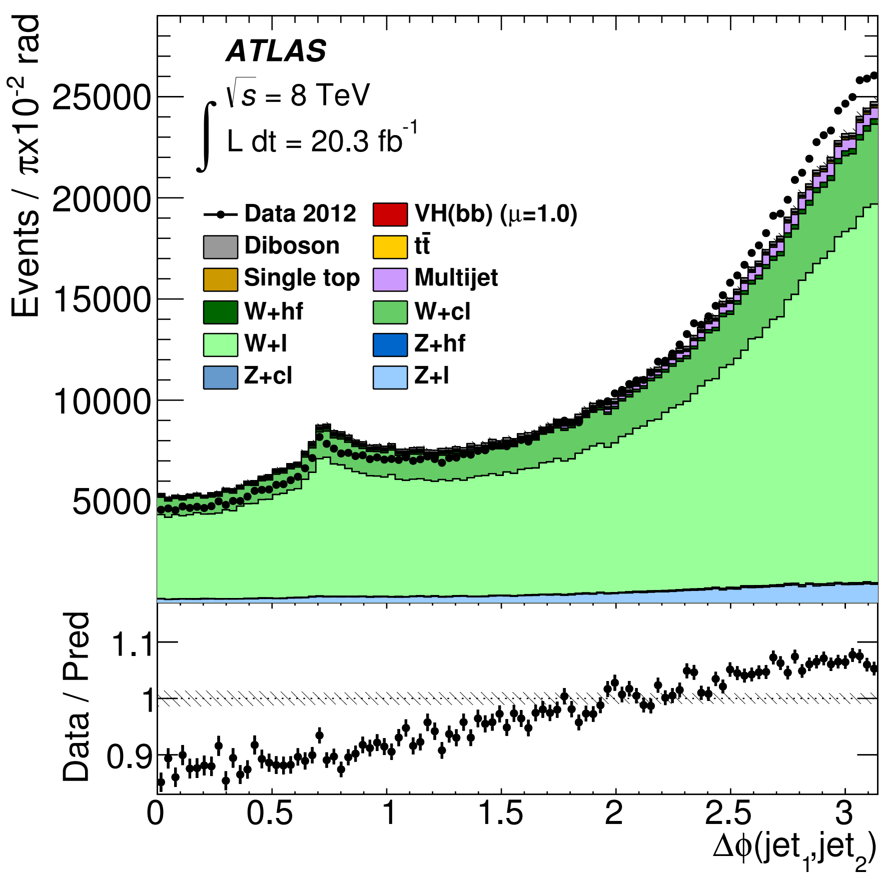
Table 3. The cross section times branching ratio (BR) and acceptance for the three channels at 8 TeV. For ZH, the $q\bar{q}$- and gg-initiated processes are shown separately. The branching ratios are calculated considering only decays to muons and electrons for $Z \to \ell\ell$, decays to all three lepton flavours for $W \to \ell\nu$ and decays to neutrinos for $Z \to \nu\nu$. The acceptance is calculated as the fraction of events remaining in the combined 2-tag signal regions of the MVA (dijet-mass analysis) after the full event selection.

VH(bb) Transformation

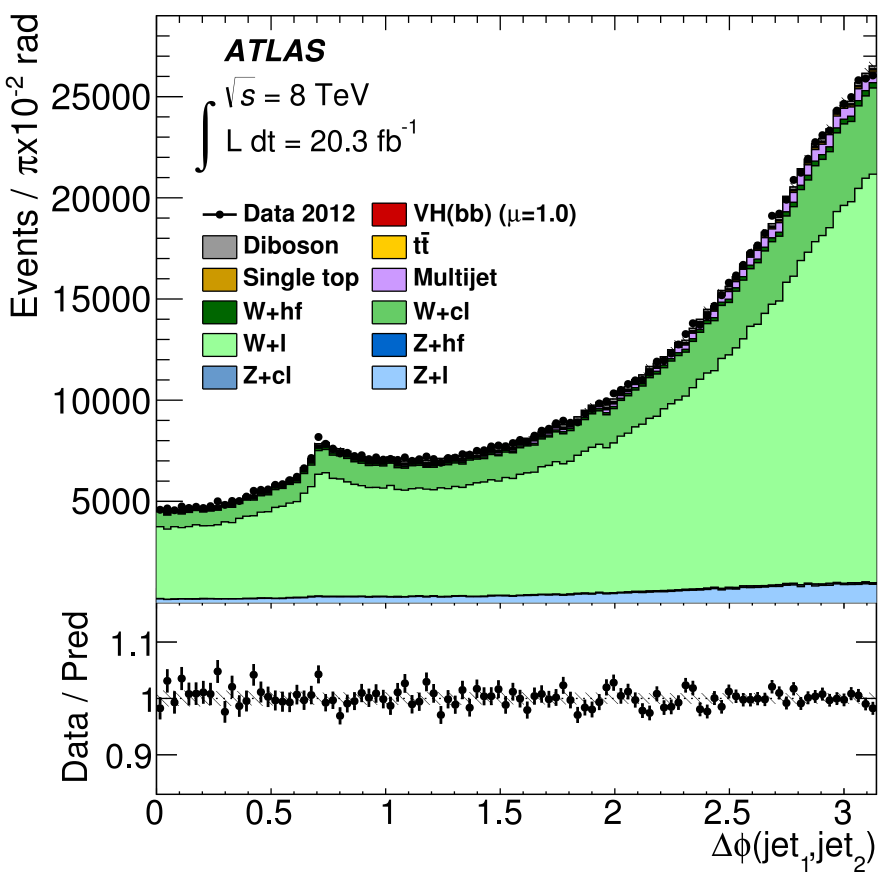


(a) (b) (c) (d)

dϕ Reweighting

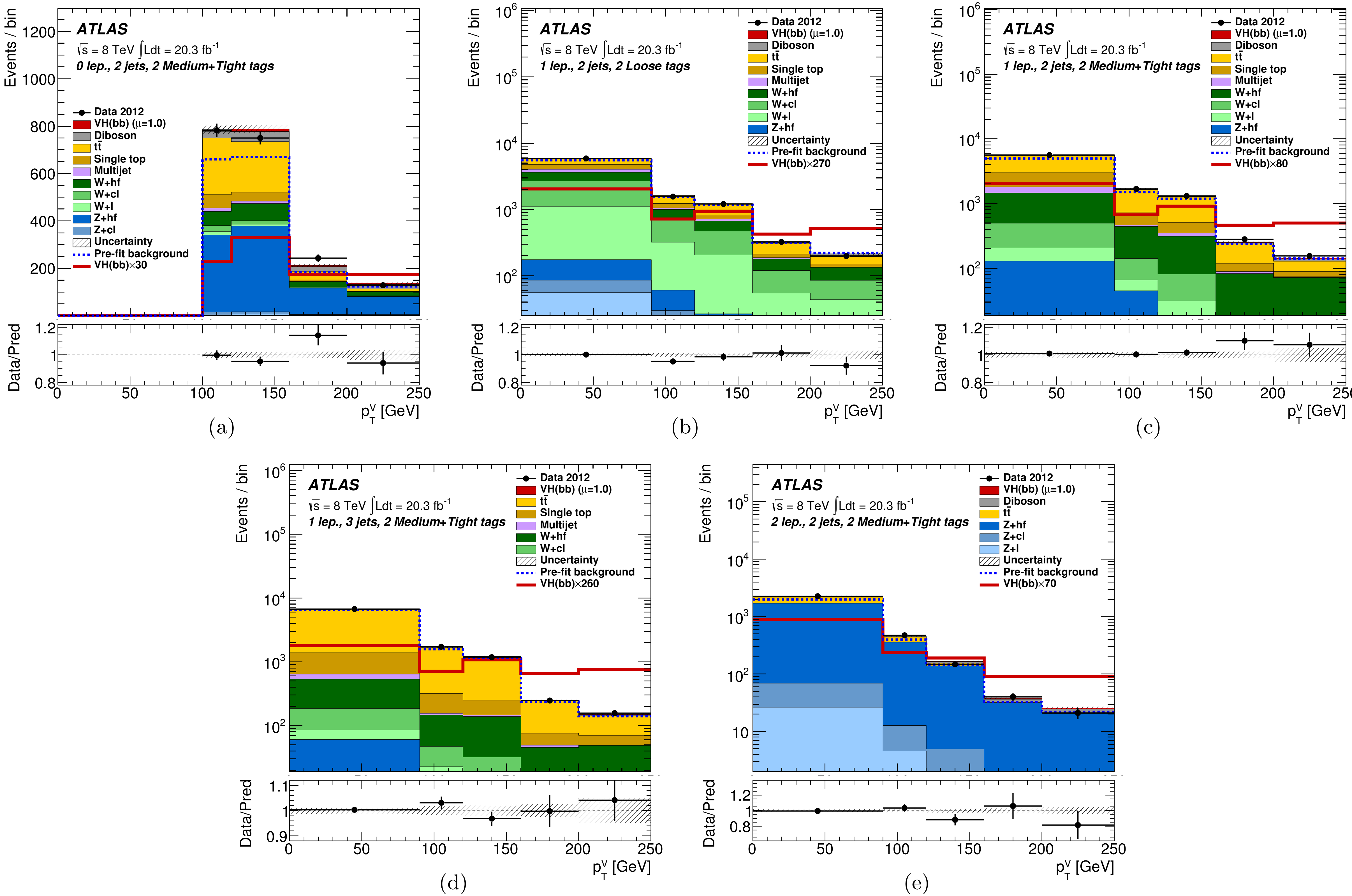


(a)



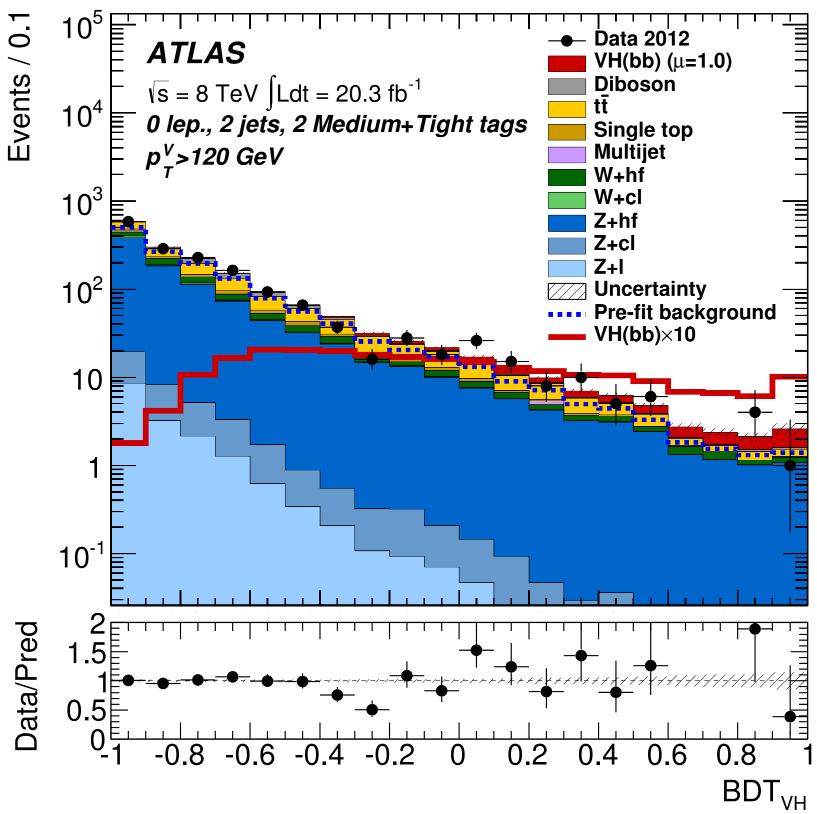
(b)

VH(bb) p_T^V

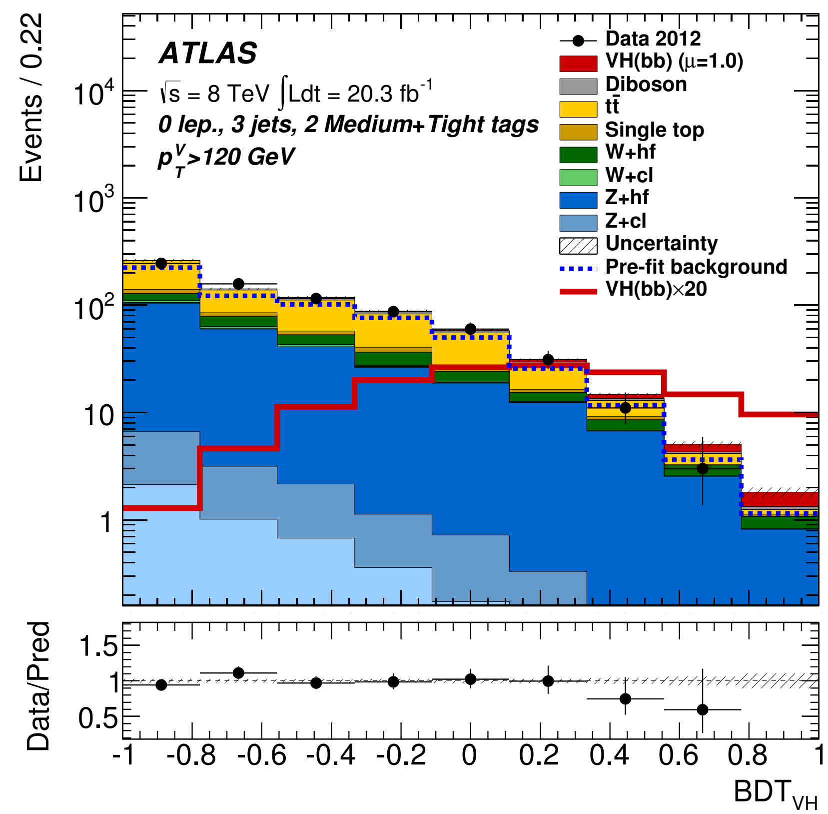


ATLAS
√s = 8 TeV ∫Ldt = 20.3 fb-1
0 lep., 2 jets, 2 Medium+Tight tags
1 lep., 2 jets, 2 Loose tags
1 lep., 2 jets, 2 Medium+Tight tags
1 lep., 3 jets, 2 Medium+Tight tags
2 lep., 2 jets, 2 Medium+Tight tags
Data 2012
VH(bb) (μ=1.0)
Diboson
tt̄
Single top
Multijet
W+hf
W+cl
W+l
Z+hf
Z+cl
Z+l
Uncertainty
Pre-fit background
VH(bb)×30
VH(bb)×270
VH(bb)×80
VH(bb)×260
VH(bb)×70
Events / bin
Data/Pred
p_T^V [GeV]
(a)
(b)
(c)
(d)
(e)

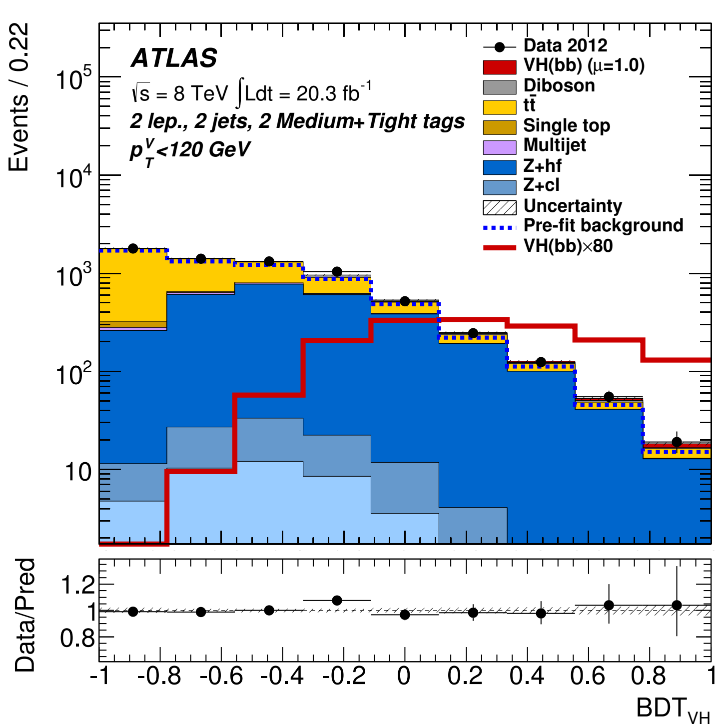
0-, 2-lepton BDT Signal Region Distributions



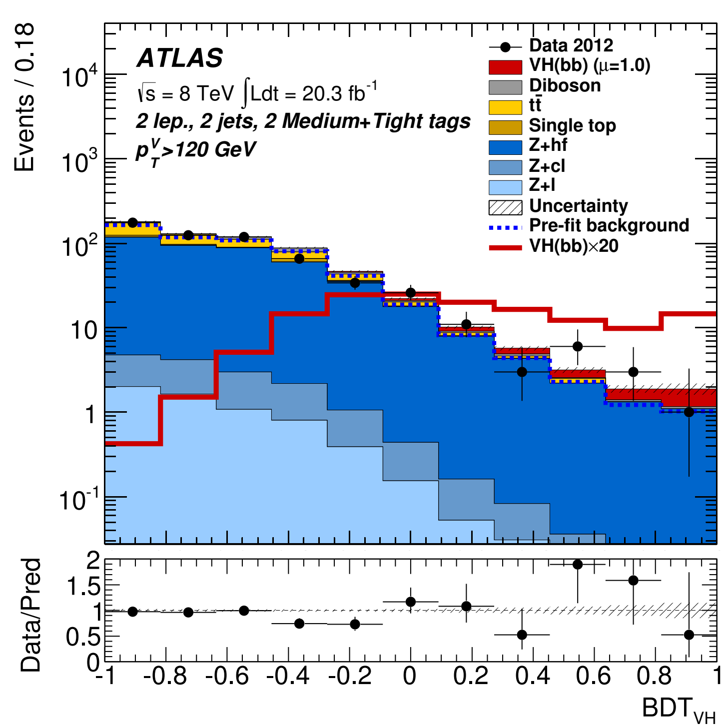
(a)



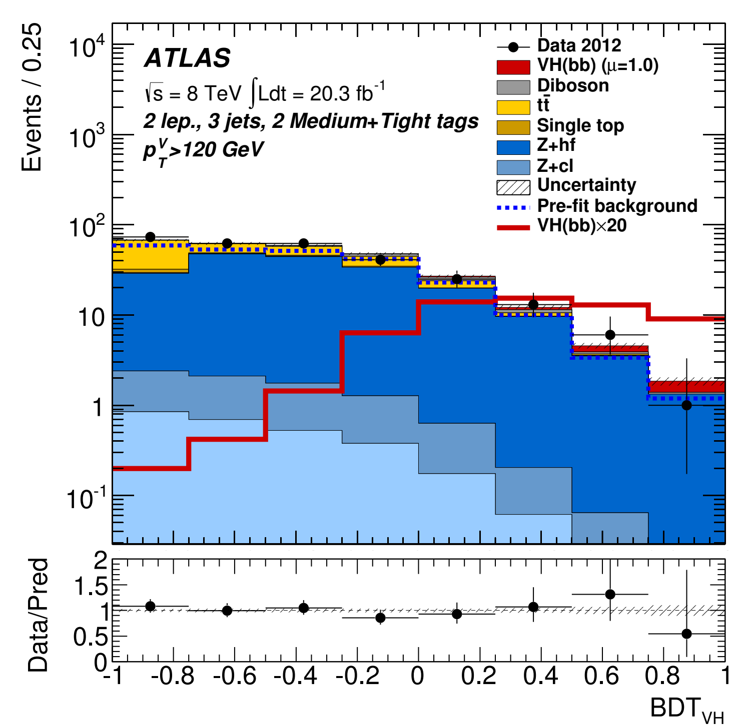
(b)



(a)

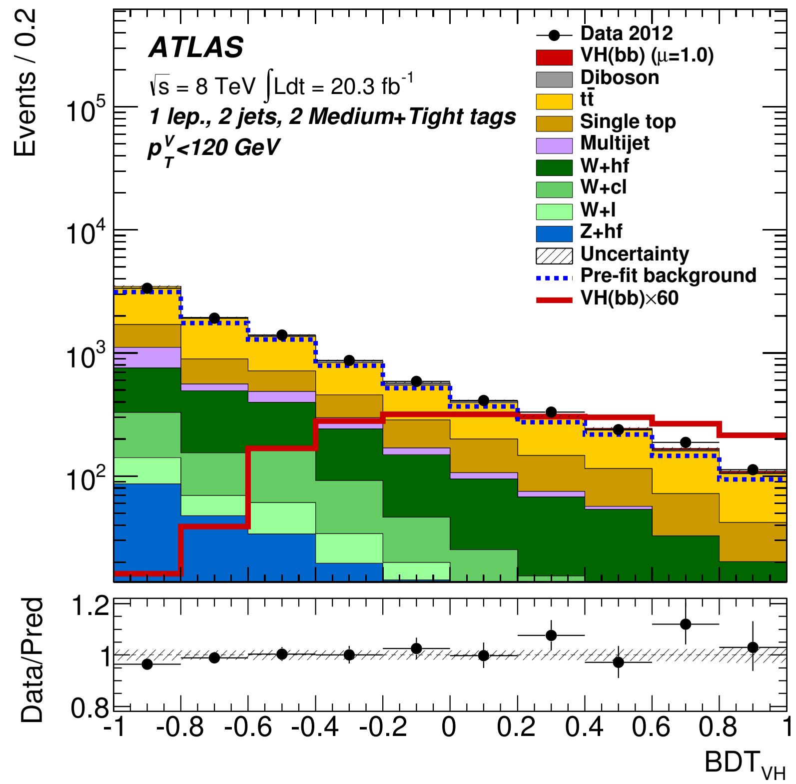


(b)

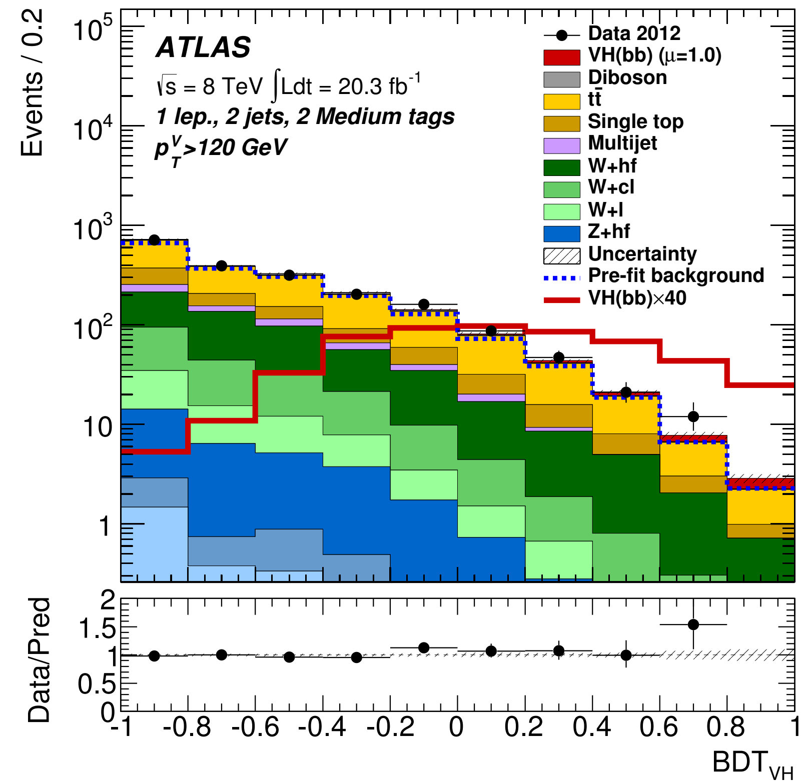


(c)

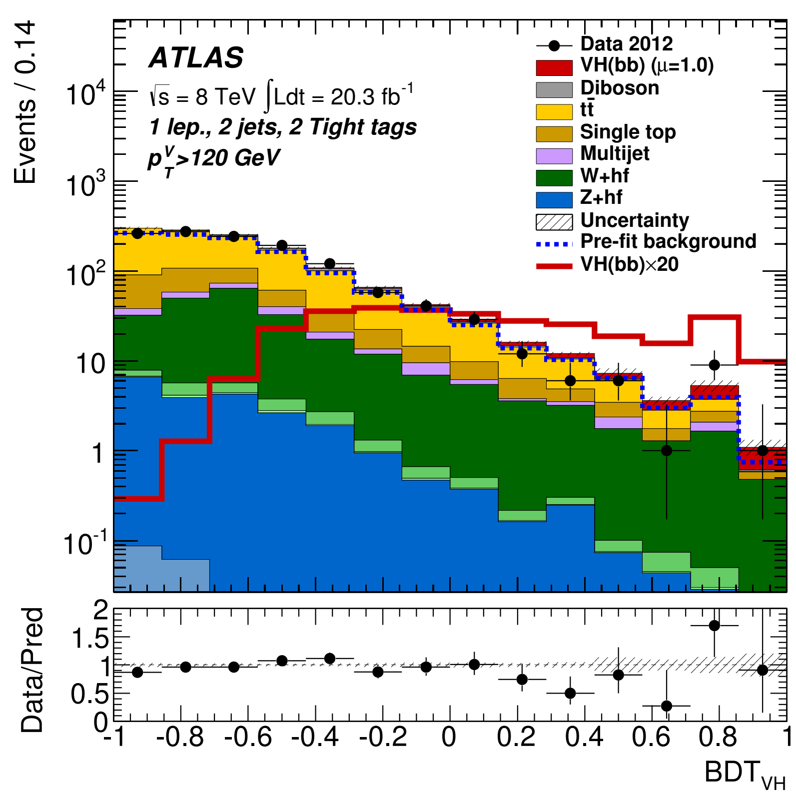
1-lepton BDT Signal Region Distributions



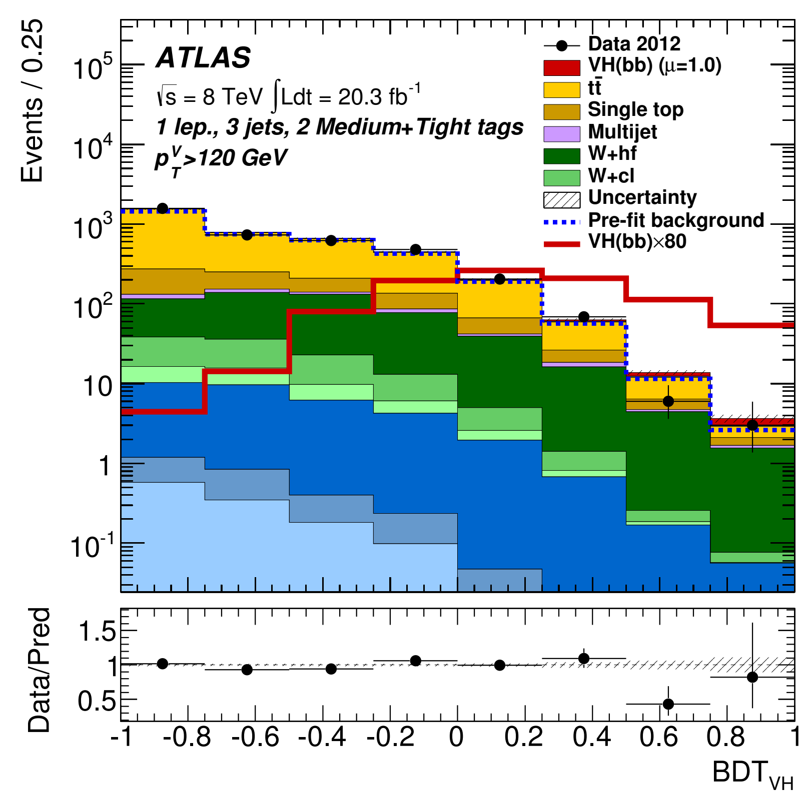
(a)



(b)

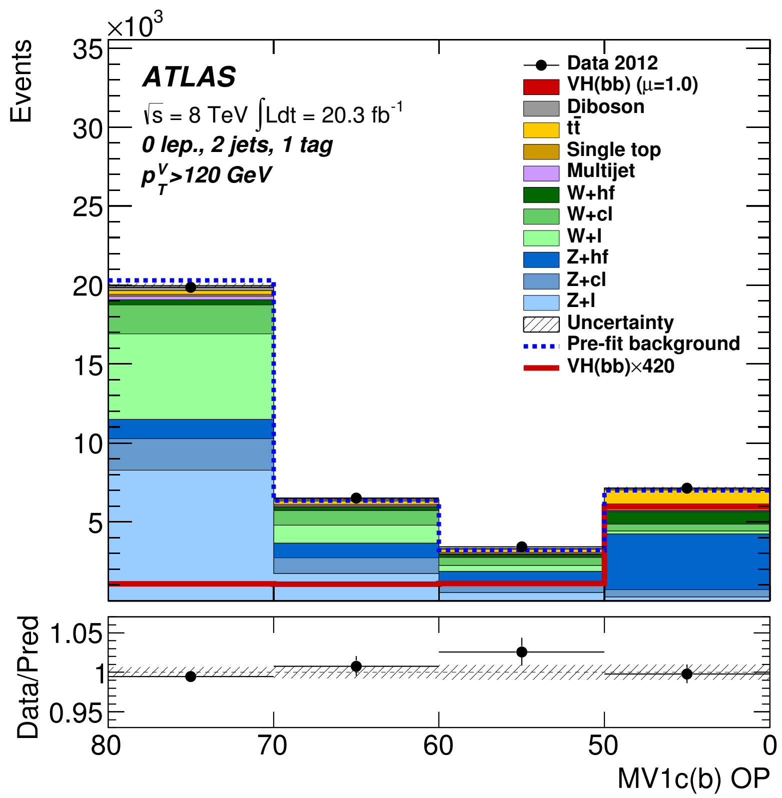


(c)

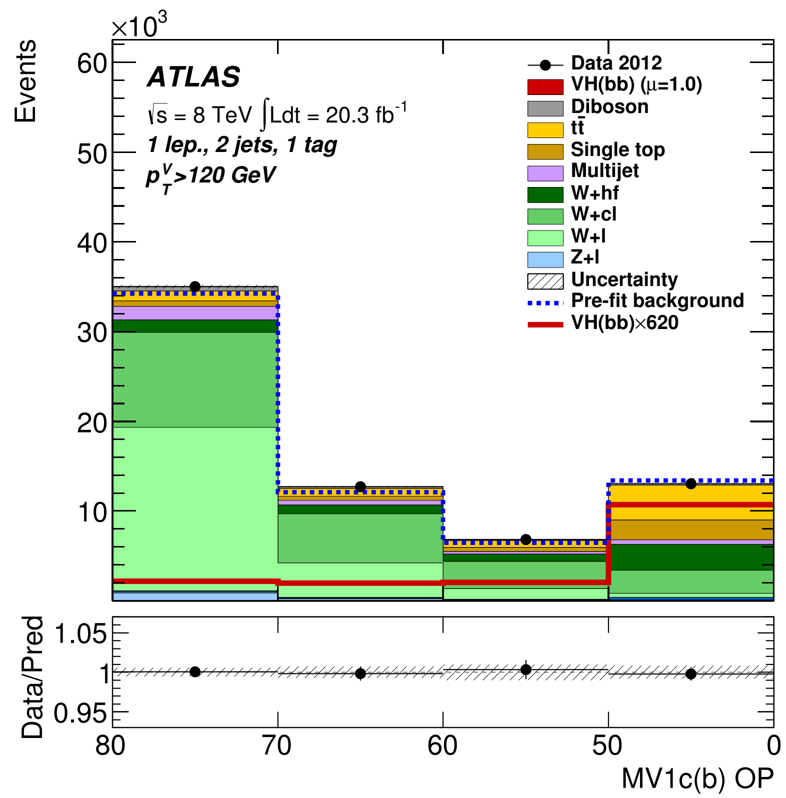


(d)

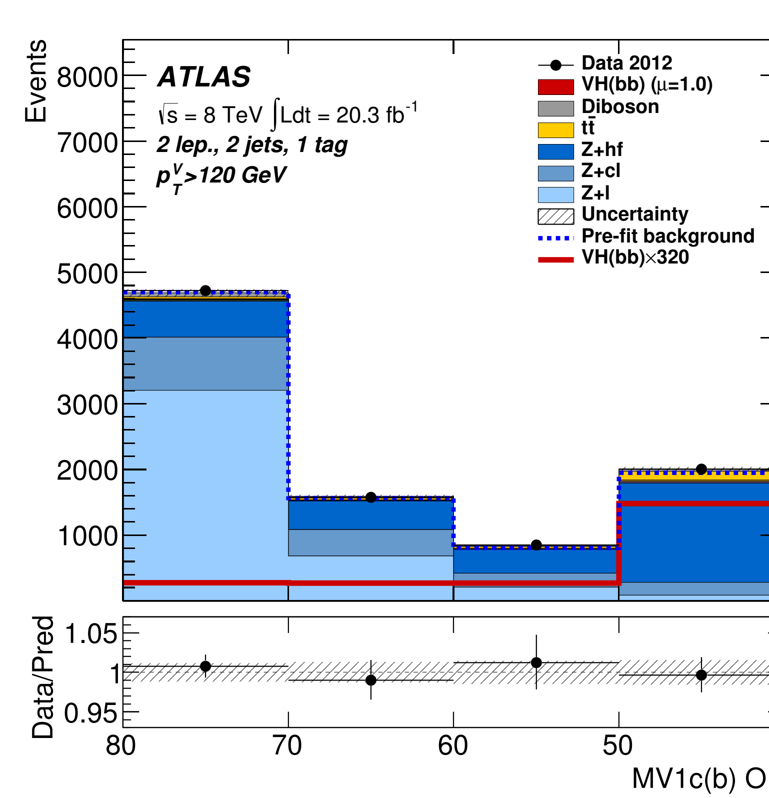
b-tagging Output



(a)



(b)

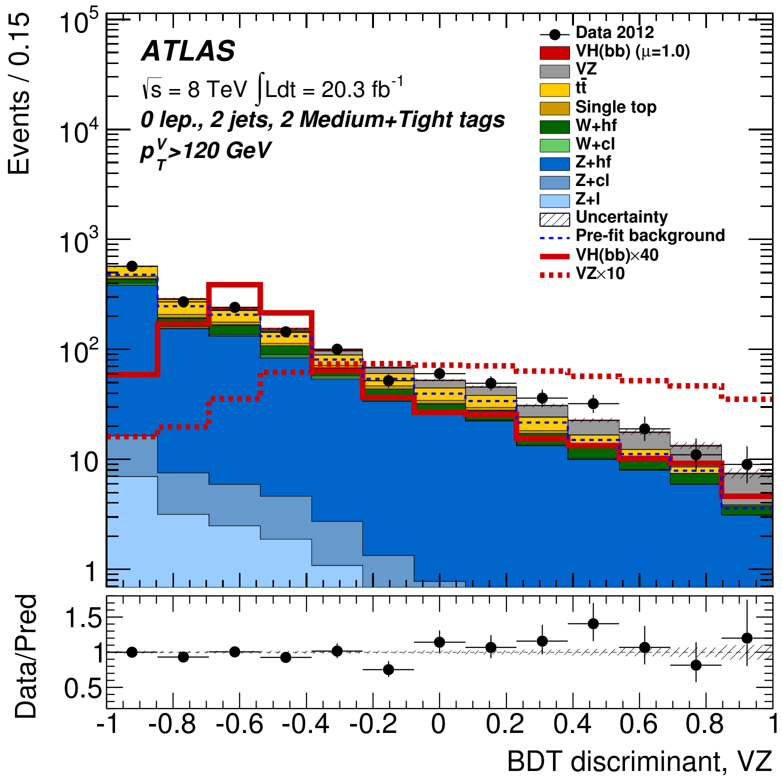


(c)

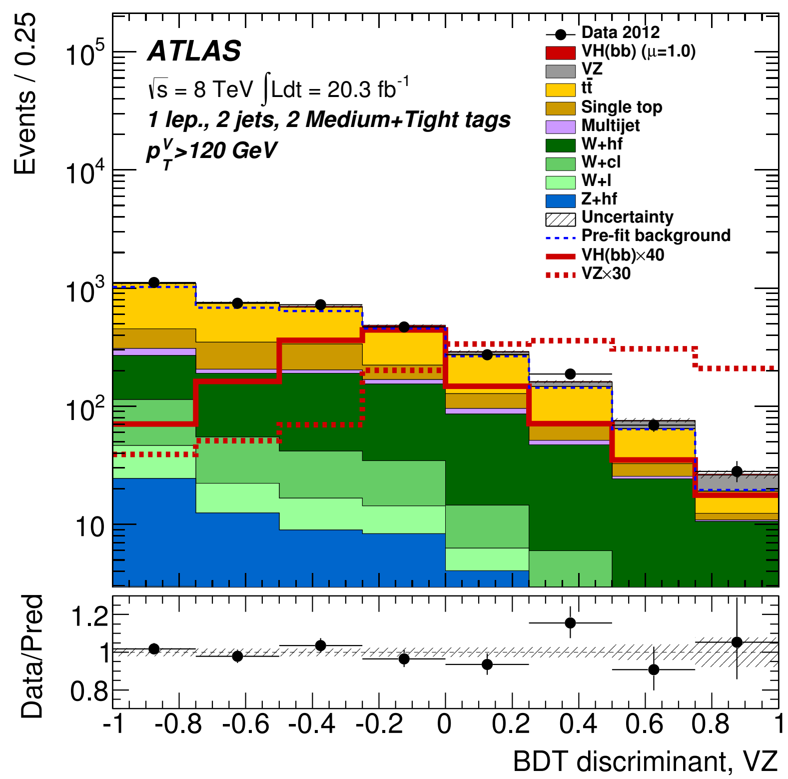
VH(bb) Fit Configuration

<table>
<tr><td></td><td colspan="3">Dijet-mass analysis</td><td colspan="3">MVA</td></tr>
<tr><td>Channel</td><td>0-lepton</td><td>1-lepton</td><td>2-lepton</td><td>0-lepton</td><td>1-lepton</td><td>2-lepton</td></tr>
<tr><td>1-tag</td><td colspan="3">$MV1c$</td><td colspan="3">$MV1c$</td></tr>
<tr><td>LL</td><td colspan="3">m_{bb}</td><td>BDT$^{(*)}$</td><td colspan="2">BDT</td></tr>
<tr><td>MM 2-tag</td><td colspan="3">m_{bb}</td><td rowspan="2">BDT$^{(*)}$</td><td>BDT</td><td rowspan="2">BDT</td></tr>
<tr><td>TT</td><td colspan="3">m_{bb}</td><td>BDT</td></tr>
</table>

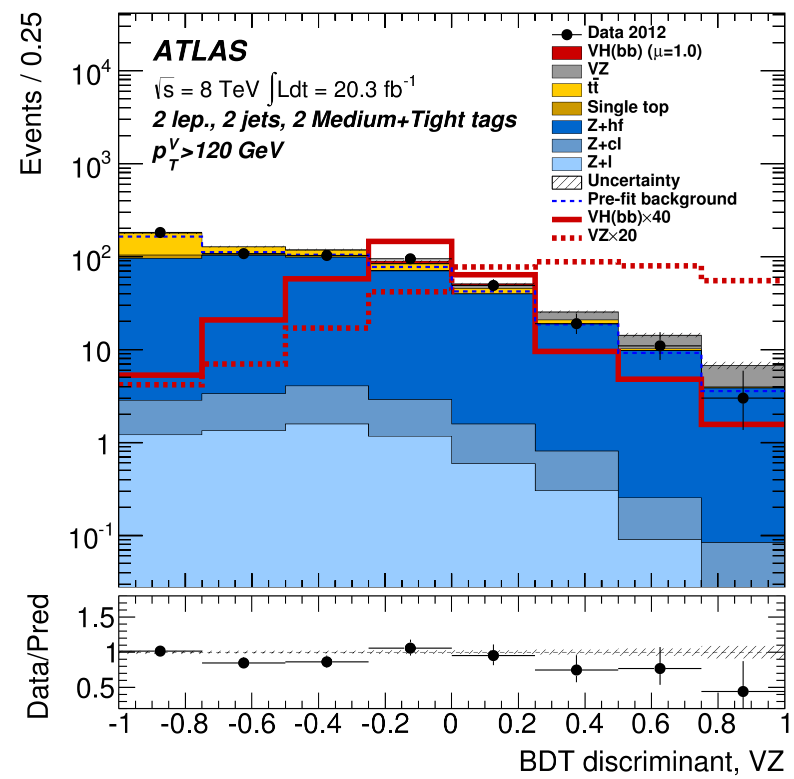
VZ BDT distributions



(a)

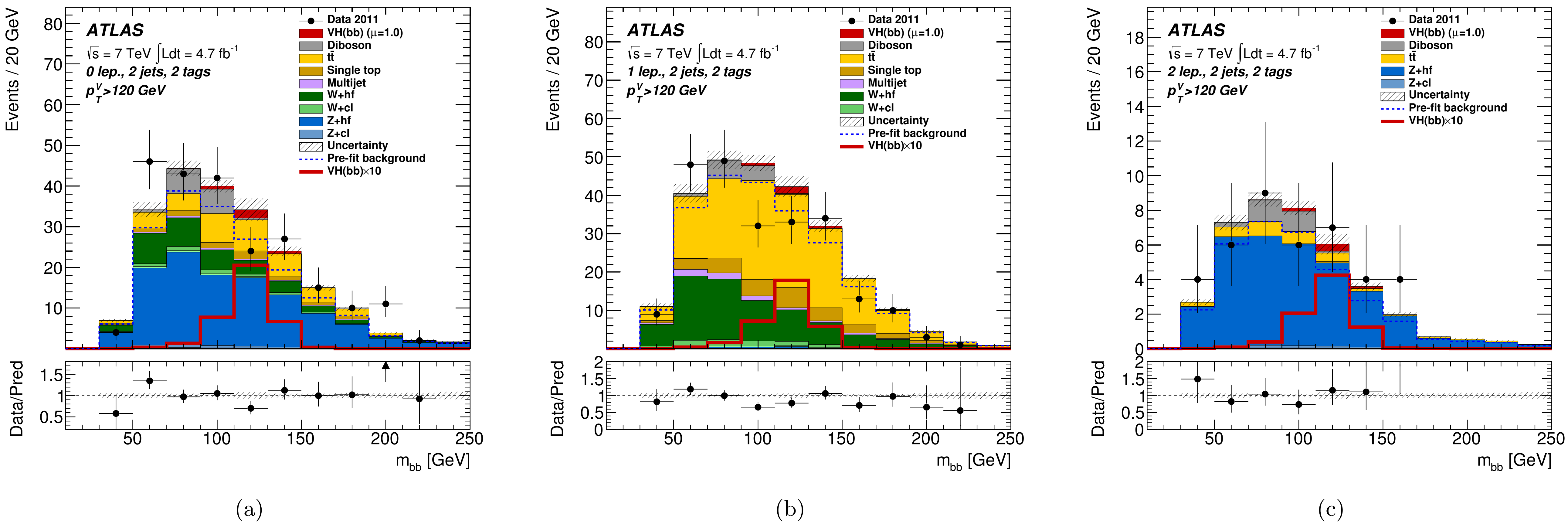


(b)

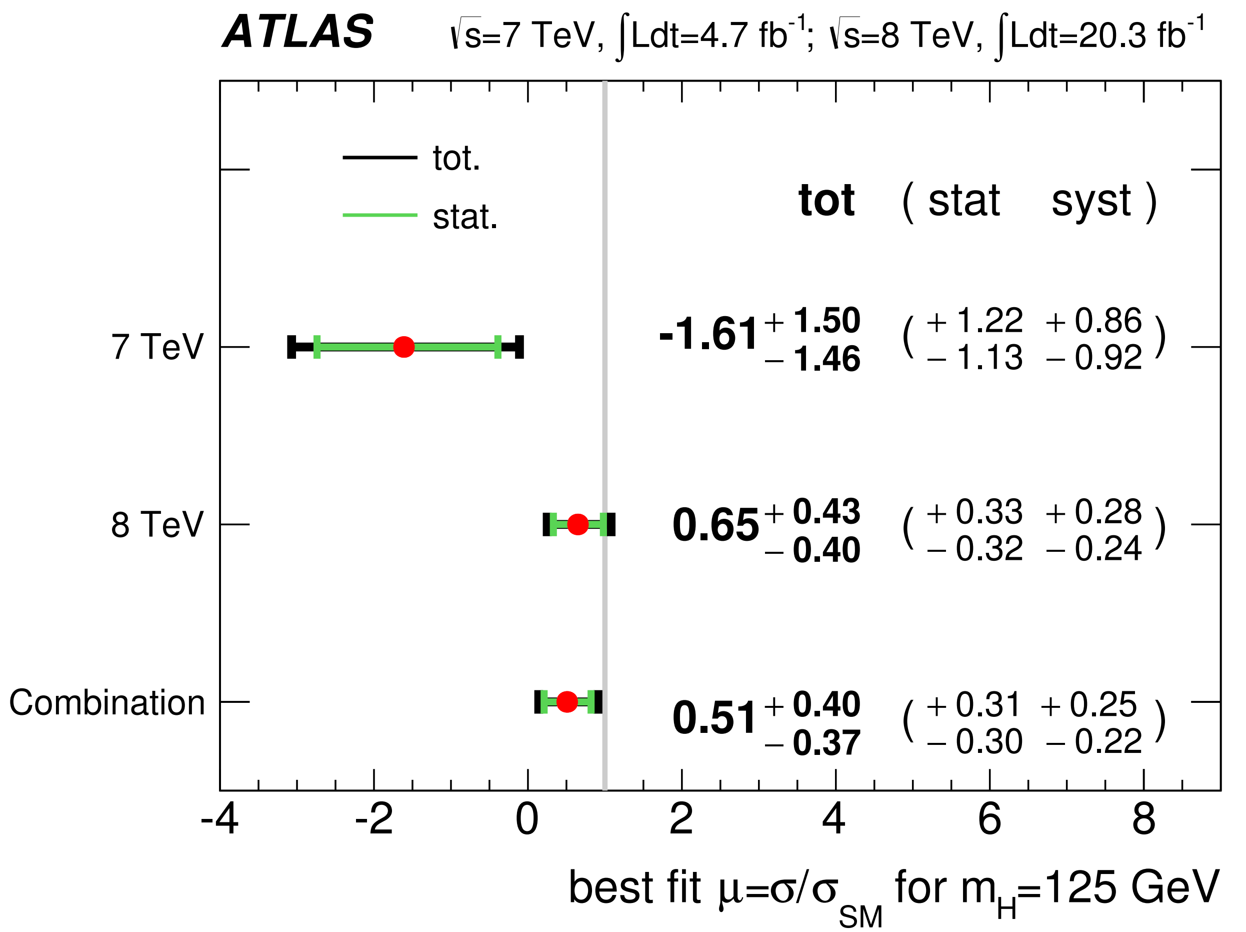


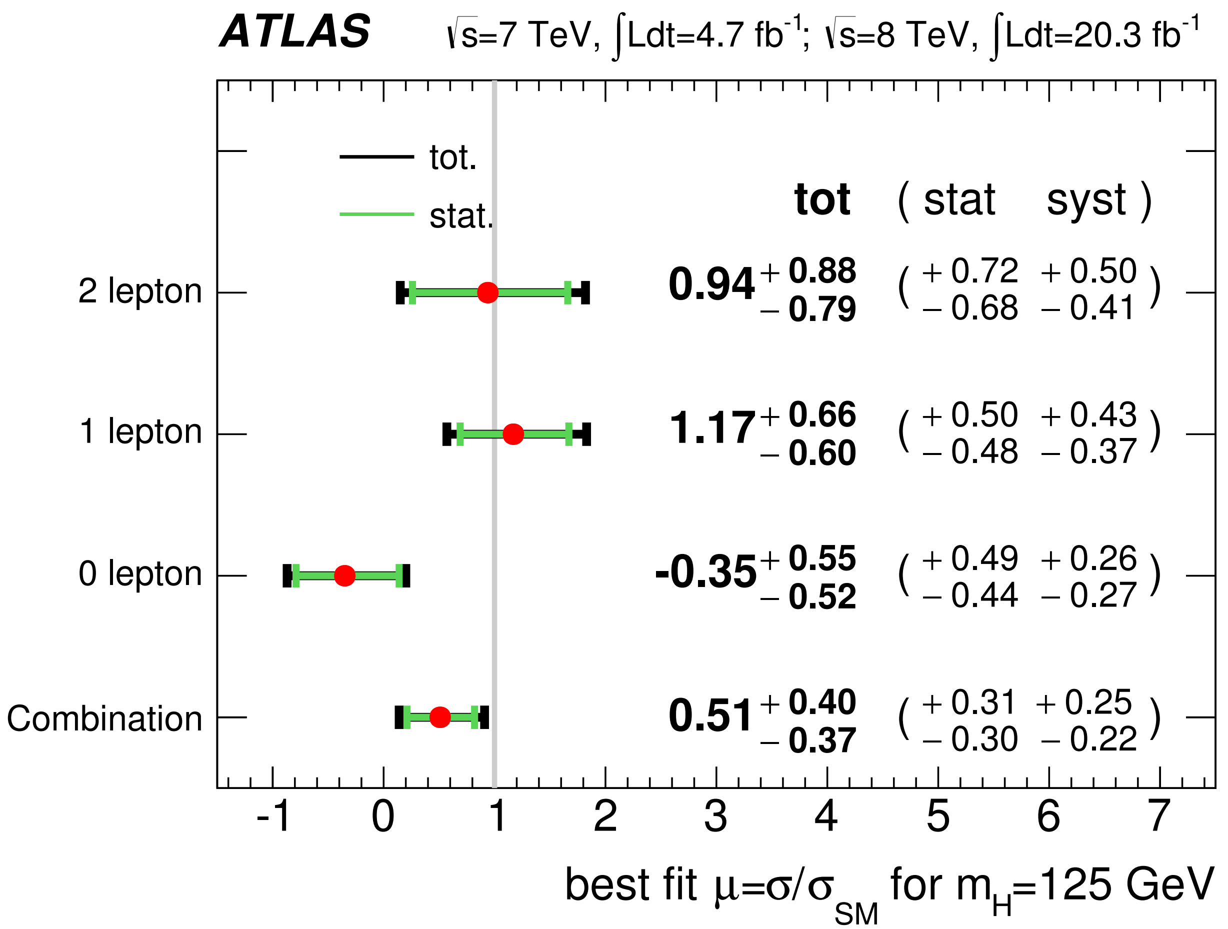
(c)

7 TeV Final Distributions

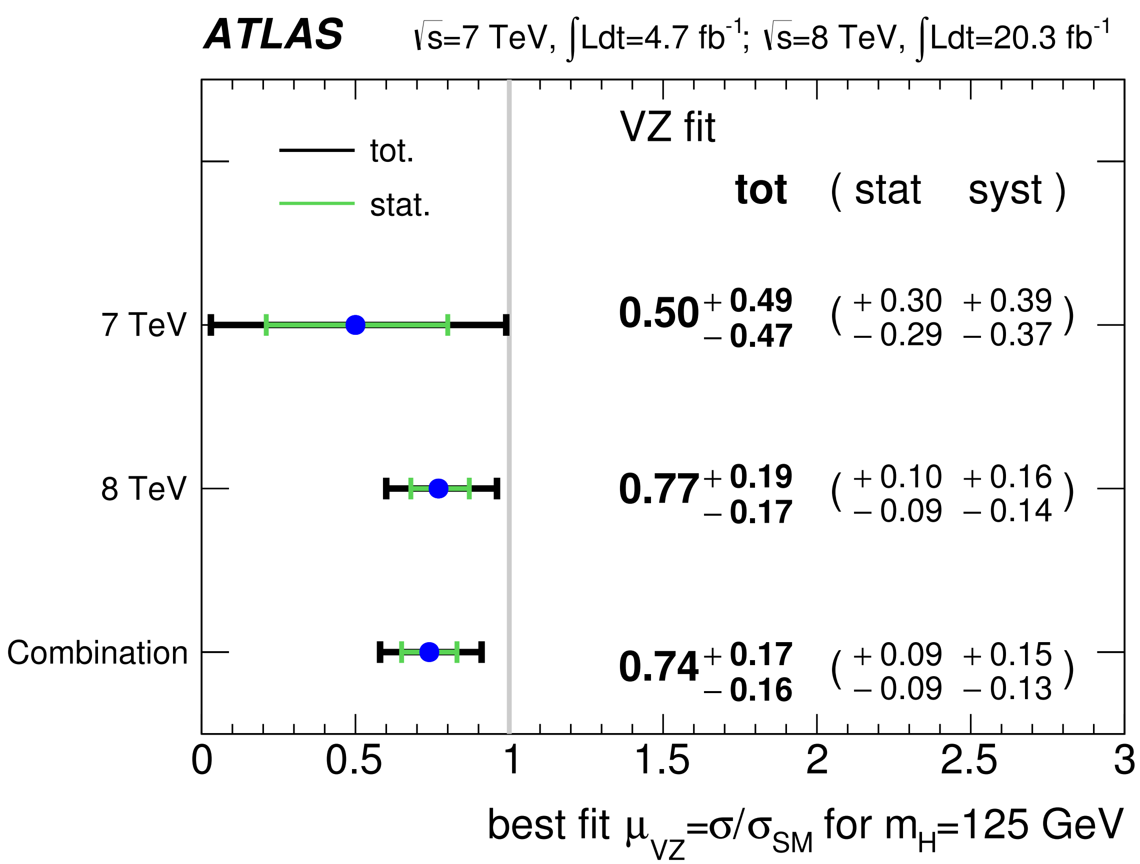


VH(bb) Results

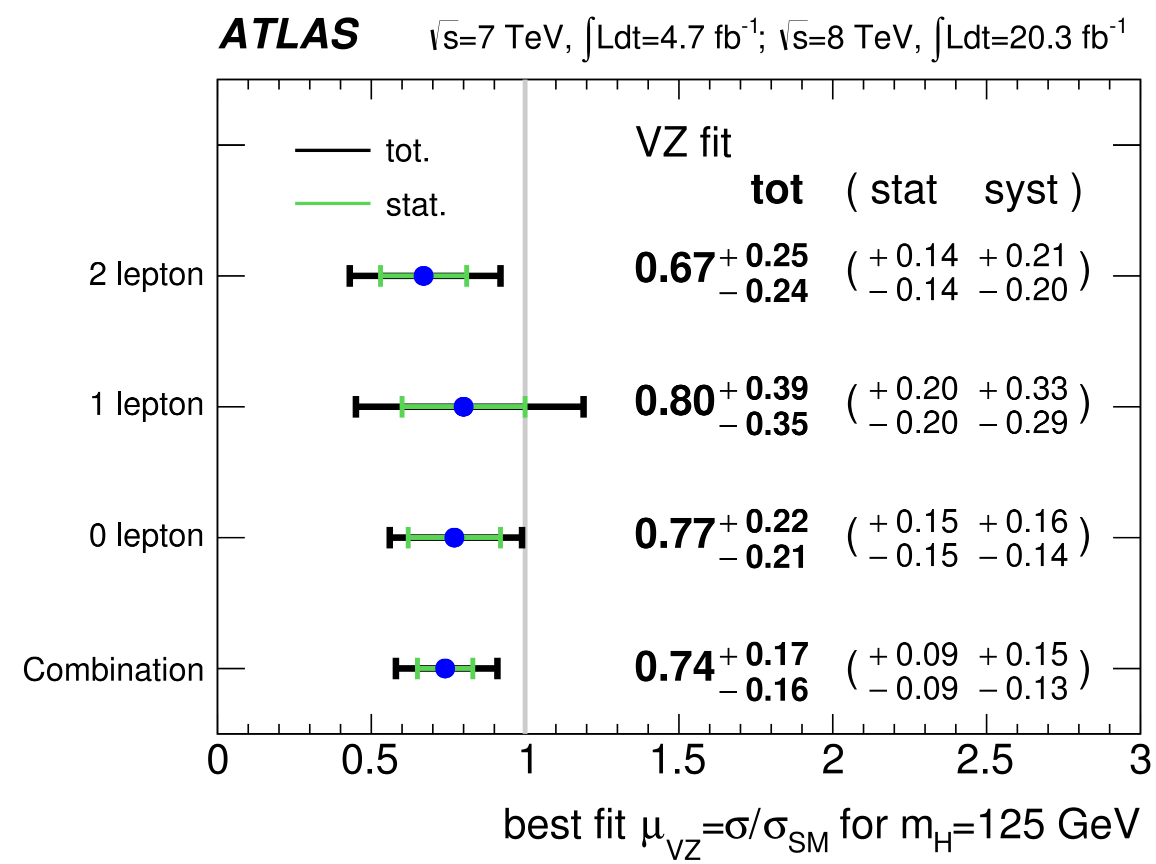




VZ Results



(a)



(b)

VH(bb) Bin Content

Process	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9
Data	368550	141166	111865	20740	5538	2245	382	41	4
Signal	29	43	96	57	58	62	32	10.7	2.3
Background	368802	140846	111831	20722	5467	2189	364	37.9	3.4
S/B	8×10^{-5}	0.0003	0.0009	0.003	0.01	0.03	0.09	0.3	0.7
W+hf	14584	10626	15297	1948	618	250	45	8.2	0.7
$W cl$	96282	30184	15227	1286	239	47	4.2	0.2	0.005
$W l$	125676	14961	3722	588	107	16	1.3	0.03	0.001
Z+hf	10758	14167	21684	7458	1178	577	130	14.8	2.2
$Z cl$	13876	11048	4419	941	61	22	2.1	0.1	0.008
$Z l$	49750	18061	3044	537	48	15	1	0.05	0.004
$t\bar{t}$	30539	24824	26729	5595	2238	922	137	10	0.3
Single top	10356	9492	14279	1494	688	252	31	2.7	0.1
Diboson	4378	1831	1247	474	186	62	9.7	1	0.2
Multijet	12603	5650	6184	400	103	26	3	0.9	0

ττ

ττ Generators

Signal ($m_H = 125$ GeV)	MC generator	$\sigma \times \mathcal{B}$ [pb] $\sqrt{s} = 8$ TeV		
ggF, $H \to \tau\tau$	POWHEG [42–45] + PYTHIA8 [46]	1.22	NNLO+NNLL	[48–53, 84]
VBF, $H \to \tau\tau$	POWHEG + PYTHIA8	0.100	(N)NLO	[57–59, 84]
WH, $H \to \tau\tau$	PYTHIA8	0.0445	NNLO	[62, 84]
ZH, $H \to \tau\tau$	PYTHIA8	0.0262	NNLO	[62, 84]
Background	**MC generator**	**$\sigma \times \mathcal{B}$ [pb] $\sqrt{s} = 8$ TeV**		
$W(\to \ell\nu)$, $(\ell = e, \mu, \tau)$	ALPGEN [77]+PYTHIA8	36800	NNLO	[85, 86]
$Z/\gamma^*(\to \ell\ell)$, 60 GeV$< m_{\ell\ell} < 2$ TeV	ALPGEN+PYTHIA8	3910	NNLO	[85, 86]
$Z/\gamma^*(\to \ell\ell)$, 10 GeV$< m_{\ell\ell} < 60$ GeV	ALPGEN+HERWIG [87]	13000	NNLO	[85, 86]
VBF $Z/\gamma^*(\to \ell\ell)$	SHERPA [88]	1.1	LO	[88]
$t\bar{t}$	POWHEG + PYTHIA8	$253^\dagger$	NNLO+NNLL	[89–94]
Single top : Wt	POWHEG + PYTHIA8	$22^\dagger$	NNLO	[95]
Single top : s-channel	POWHEG + PYTHIA8	$5.6^\dagger$	NNLO	[96]
Single top : t-channel	AcerMC [80]+PYTHIA6 [73]	$87.8^\dagger$	NNLO	[97]
$q\bar{q} \to WW$	ALPGEN+HERWIG	$54^\dagger$	NLO	[98]
$gg \to WW$	GG2WW [79]+HERWIG	$1.4^\dagger$	NLO	[79]
WZ, ZZ	HERWIG	$30^\dagger$	NLO	[98]
$H \to WW$	same as for $H \to \tau\tau$ signal	$4.7^\dagger$		

ττ Event Selection

Channel	Preselection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	Exactly two isolated opposite-sign leptons Events with $\tau_{\rm had}$ candidates are rejected 30 GeV$< m_{\tau\tau}^{\rm vis} < 100$ (75) GeV for DF (SF) events $\Delta\phi_{\ell\ell} < 2.5$ $E_{\rm T}^{\rm miss} > 20$ (40) GeV for DF (SF) events $E_{\rm T}^{\rm miss,HPTO} > 40$ GeV for SF events $p_{\rm T}^{\ell_1} + p_{\rm T}^{\ell_2} > 35$ GeV Events with a b-tagged jet with $p_{\rm T} > 25$ GeV are rejected $0.1 < x_{\tau_1}, x_{\tau_2} < 1$ $m_{\tau\tau}^{\rm coll} > m_Z - 25$ GeV
$\tau_{\rm lep}\tau_{\rm had}$	Exactly one isolated lepton and one medium $\tau_{\rm had}$ candidate with opposite charges $m_{\rm T} < 70$ GeV Events with a b-tagged jet with $p_{\rm T} > 30$ GeV are rejected
$\tau_{\rm had}\tau_{\rm had}$	One isolated medium and one isolated tight opposite-sign $\tau_{\rm had}$-candidate Events with leptons are vetoed $E_{\rm T}^{\rm miss} > 20$ GeV $E_{\rm T}^{\rm miss}$ points between the two visible taus in ϕ, or $\min[\Delta\phi(\tau, E_{\rm T}^{\rm miss})] < \pi/4$ $0.8 < \Delta R(\tau_{{\rm had}_1}, \tau_{{\rm had}_2}) < 2.4$ $\Delta\eta(\tau_{{\rm had}_1}, \tau_{{\rm had}_2}) < 1.5$
Channel	VBF category selection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	At least two jets with $p_{\rm T}^{j_1} > 40$ GeV and $p_{\rm T}^{j_2} > 30$ GeV $\Delta\eta(j_1, j_2) > 2.2$
$\tau_{\rm lep}\tau_{\rm had}$	At least two jets with $p_{\rm T}^{j_1} > 50$ GeV and $p_{\rm T}^{j_2} > 30$ GeV $\Delta\eta(j_1, j_2) > 3.0$ $m_{\tau\tau}^{\rm vis} > 40$ GeV
$\tau_{\rm had}\tau_{\rm had}$	At least two jets with $p_{\rm T}^{j_1} > 50$ GeV and $p_{\rm T}^{j_2} > 30$ GeV $p_{\rm T}^{j_2} > 35$ GeV for jets with $\|\eta\| > 2.4$ $\Delta\eta(j_1, j_2) > 2.0$
Channel	Boosted category selection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	At least one jet with $p_{\rm T} > 40$ GeV
All	Failing the VBF selection $p_{\rm T}^{H} > 100$ GeV

ττ Triggers

Trigger	Trigger level thresholds, p_{T} [GeV]	Analysis level thresholds [GeV] $\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	Analysis level thresholds [GeV] $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	Analysis level thresholds [GeV] $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$
$\sqrt{s} = 7$ TeV				
Single electron	20–22	$e\mu$: $p_{\mathrm{T}}^{e} > 22-24$ $p_{\mathrm{T}}^{\mu} > 10$	$e\tau$: $p_{\mathrm{T}}^{e} > 25$ $p_{\mathrm{T}}^{\tau} > 20$	–
Single muon	18	$\mu\mu$: $p_{\mathrm{T}}^{\mu_1} > 20$ $p_{\mathrm{T}}^{\mu_2} > 10$ $e\mu$: $p_{\mathrm{T}}^{\mu} > 20$ $p_{\mathrm{T}}^{e} > 15$	$\mu\tau$: $p_{\mathrm{T}}^{\mu} > 22$ $p_{\mathrm{T}}^{\tau} > 20$	–
Di-electron	12/12	ee: $p_{\mathrm{T}}^{e_1} > 15$ $p_{\mathrm{T}}^{e_2} > 15$	–	–
Di-τ_{had}	29/20	–	–	$\tau\tau$: $p_{\mathrm{T}}^{\tau_1} > 35$ $p_{\mathrm{T}}^{\tau_2} > 25$
$\sqrt{s} = 8$ TeV				
Single electron	24	$e\mu$: $p_{\mathrm{T}}^{e} > 26$ $p_{\mathrm{T}}^{\mu} > 10$ ee: $p_{\mathrm{T}}^{e_1} > 26$ $p_{\mathrm{T}}^{e_2} > 15$	$e\tau$: $p_{\mathrm{T}}^{e} > 26$ $p_{\mathrm{T}}^{\tau} > 20$	–
Single muon	24	–	$\mu\tau$: $p_{\mathrm{T}}^{\mu} > 26$ $p_{\mathrm{T}}^{\tau} > 20$	–
Di-electron	12/12	ee: $p_{\mathrm{T}}^{e_1} > 15$ $p_{\mathrm{T}}^{e_2} > 15$	–	–
Di-muon	18/8	$\mu\mu$: $p_{\mathrm{T}}^{\mu_1} > 20$ $p_{\mathrm{T}}^{\mu_2} > 10$	–	–
Electron+muon	12/8	$e\mu$: $p_{\mathrm{T}}^{e} > 15$ $p_{\mathrm{T}}^{\mu} > 10$	–	–
Di-τ_{had}	29/20	–	–	$\tau\tau$: $p_{\mathrm{T}}^{\tau_1} > 35$ $p_{\mathrm{T}}^{\tau_2} > 25$

ττ Categories

Channel	Preselection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	Exactly two isolated opposite-sign leptons Events with $\tau_{\rm had}$ candidates are rejected 30 GeV $< m_{\tau\tau}^{\rm vis} <$ 100 (75) GeV for DF (SF) events $\Delta\phi_{\ell\ell} < 2.5$ $E_{\rm T}^{\rm miss} >$ 20 (40) GeV for DF (SF) events $E_{\rm T}^{\rm miss,HPTO} >$ 40 GeV for SF events $p_{\rm T}^{\ell_1} + p_{\rm T}^{\ell_2} >$ 35 GeV Events with a b-tagged jet with $p_{\rm T} >$ 25 GeV are rejected $0.1 < x_{\tau_1}, x_{\tau_2} < 1$ $m_{\tau\tau}^{\rm coll} > m_Z - 25$ GeV
$\tau_{\rm lep}\tau_{\rm had}$	Exactly one isolated lepton and one medium $\tau_{\rm had}$ candidate with opposite charges $m_{\rm T} <$ 70 GeV Events with a b-tagged jet with $p_{\rm T} >$ 30 GeV are rejected
$\tau_{\rm had}\tau_{\rm had}$	One isolated medium and one isolated tight opposite-sign $\tau_{\rm had}$-candidate Events with leptons are vetoed $E_{\rm T}^{\rm miss} >$ 20 GeV $E_{\rm T}^{\rm miss}$ points between the two visible taus in ϕ, or $\min[\Delta\phi(\tau, E_{\rm T}^{\rm miss})] < \pi/4$ $0.8 < \Delta R(\tau_{\rm had_1}, \tau_{\rm had_2}) < 2.4$ $\Delta\eta(\tau_{\rm had_1}, \tau_{\rm had_2}) < 1.5$
Channel	VBF category selection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	At least two jets with $p_{\rm T}^{j_1} >$ 40 GeV and $p_{\rm T}^{j_2} >$ 30 GeV $\Delta\eta(j_1, j_2) > 2.2$
$\tau_{\rm lep}\tau_{\rm had}$	At least two jets with $p_{\rm T}^{j_1} >$ 50 GeV and $p_{\rm T}^{j_2} >$ 30 GeV $\Delta\eta(j_1, j_2) > 3.0$ $m_{\tau\tau}^{\rm vis} >$ 40 GeV
$\tau_{\rm had}\tau_{\rm had}$	At least two jets with $p_{\rm T}^{j_1} >$ 50 GeV and $p_{\rm T}^{j_2} >$ 30 GeV $p_{\rm T}^{j_2} >$ 35 GeV for jets with $\|\eta\| > 2.4$ $\Delta\eta(j_1, j_2) > 2.0$
Channel	Boosted category selection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	At least one jet with $p_{\rm T}>$ 40 GeV
All	Failing the VBF selection $p_{\rm T}^{H} >$ 100 GeV

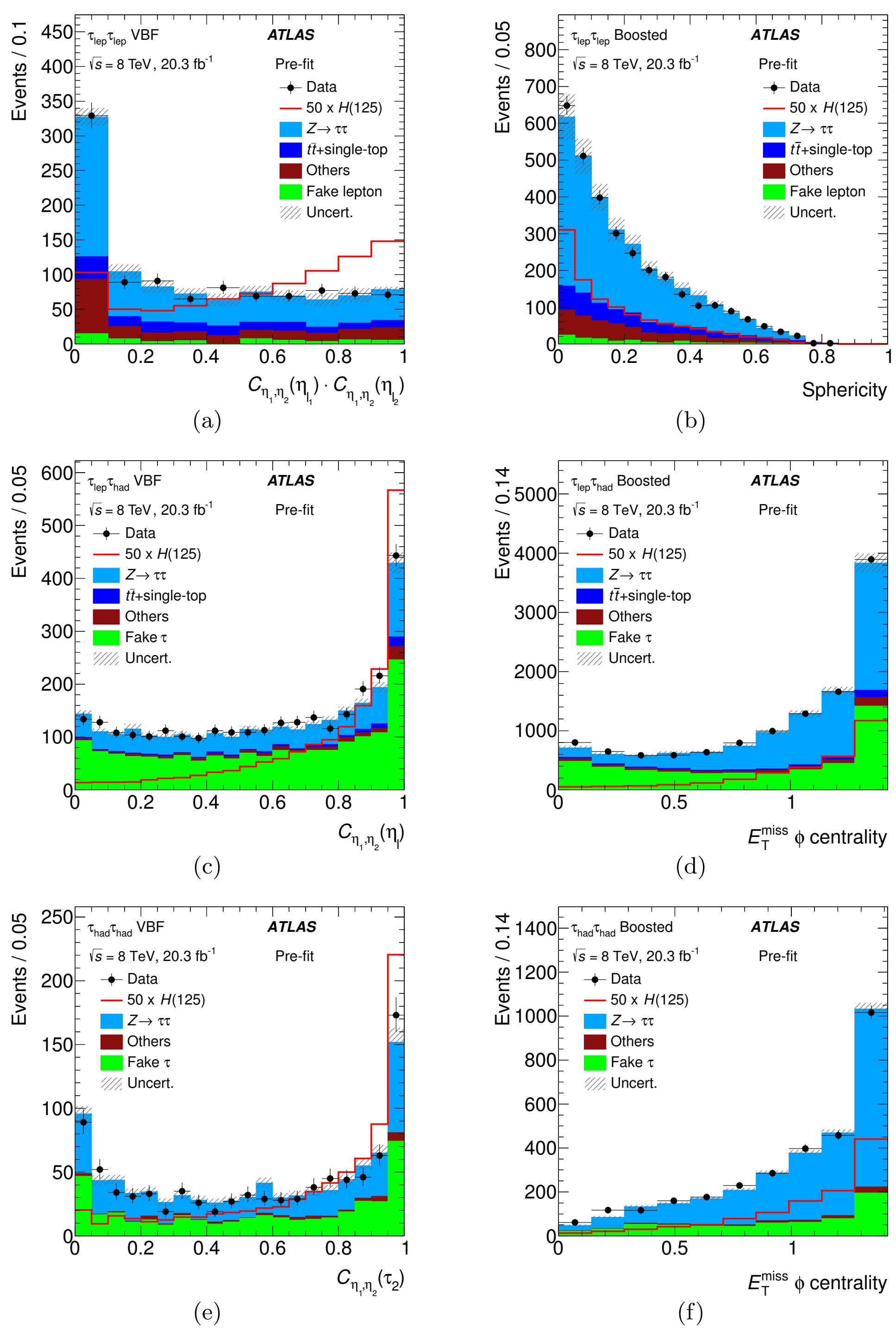
BDT Variables

Variable	VBF			Boosted		
	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$
$m_{\tau\tau}^{\mathrm{MMC}}$	●	●	●	●	●	●
$\Delta R(\tau_1, \tau_2)$	●	●	●		●	●
$\Delta\eta(j_1, j_2)$	●	●	●			
m_{j_1,j_2}	●	●	●			
$\eta_{j_1} \times \eta_{j_2}$		●	●			
$p_{\mathrm{T}}^{\mathrm{Total}}$		●	●			
Sum p_{T}					●	●
$p_{\mathrm{T}}^{\tau_1}/p_{\mathrm{T}}^{\tau_2}$					●	●
$E_{\mathrm{T}}^{\mathrm{miss}}\phi$ centrality		●	●	●	●	●
m_{ℓ,ℓ,j_1}				●		
m_{ℓ_1,ℓ_2}				●		
$\Delta\phi(\ell_1, \ell_2)$				●		
Sphericity				●		
$p_{\mathrm{T}}^{\ell_1}$				●		
$p_{\mathrm{T}}^{j_1}$				●		
$E_{\mathrm{T}}^{\mathrm{miss}}/p_{\mathrm{T}}^{\ell_2}$				●		
m_{T}		●			●	
$\min(\Delta\eta_{\ell_1\ell_2,\mathrm{jets}})$	●					
$C_{\eta_1,\eta_2}(\eta_{\ell_1}) \cdot C_{\eta_1,\eta_2}(\eta_{\ell_2})$	●					
$C_{\eta_1,\eta_2}(\eta_{\ell})$		●				
$C_{\eta_1,\eta_2}(\eta_{j_3})$	●					
$C_{\eta_1,\eta_2}(\eta_{\tau_1})$			●			
$C_{\eta_1,\eta_2}(\eta_{\tau_2})$			●			

BDT Variable Definition

- $\Delta R(\tau_1, \tau_2)$: the distance ΔR between the two leptons, between the lepton and τ_{had}, or between the two τ_{had} candidates, depending on the decay mode.

- $p_{\mathrm{T}}^{\mathrm{Total}}$: magnitude of the vector sum of the transverse momenta of the visible tau decay products, the two leading jets, and $E_{\mathrm{T}}^{\mathrm{miss}}$.



- Sum p_{T}: scalar sum of the p_{T} of the visible components of the tau decay products and of the jets.

- $E_{\mathrm{T}}^{\mathrm{miss}}\phi$ centrality: a variable that quantifies the relative angular position of the missing transverse momentum with respect to the visible tau decay products in the transverse plane. The transverse plane is transformed such that the direction of the tau decay products are orthogonal, and that the smaller ϕ angle between the tau decay products defines the positive quadrant of the transformed plane. The $E_{\mathrm{T}}^{\mathrm{miss}}\phi$ centrality is defined as the sum of the x- and y-components of the $E_{\mathrm{T}}^{\mathrm{miss}}$ unit vector in this transformed plane.

- Sphericity: a variable that describes the isotropy of the energy flow in the event [101]. It is based on the quadratic momentum tensor

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\vec{p_i}^2|}. \tag{5.1}$$

In this equation, α and β are the indices of the tensor. The summation is performed over the momenta of the selected leptons and jets in the event. The sphericity of the event (S) is then defined in terms of the two smallest eigenvalues of this tensor, λ_2 and λ_3,

$$S = \frac{3}{2}(\lambda_2 + \lambda_3). \tag{5.2}$$

- $\min(\Delta\eta_{\ell_1\ell_2,\mathrm{jets}})$: the minimum $\Delta\eta$ between the dilepton system and either of the two jets.

- Object η centrality: a variable that quantifies the η position of an object (an isolated lepton, a τ_{had} candidate or a jet) with respect to the two leading jets in the event. It is defined as

$$C_{\eta_1,\eta_2}(\eta) = \exp\left[\frac{-4}{(\eta_1-\eta_2)^2}\left(\eta - \frac{\eta_1+\eta_2}{2}\right)^2\right], \tag{5.3}$$

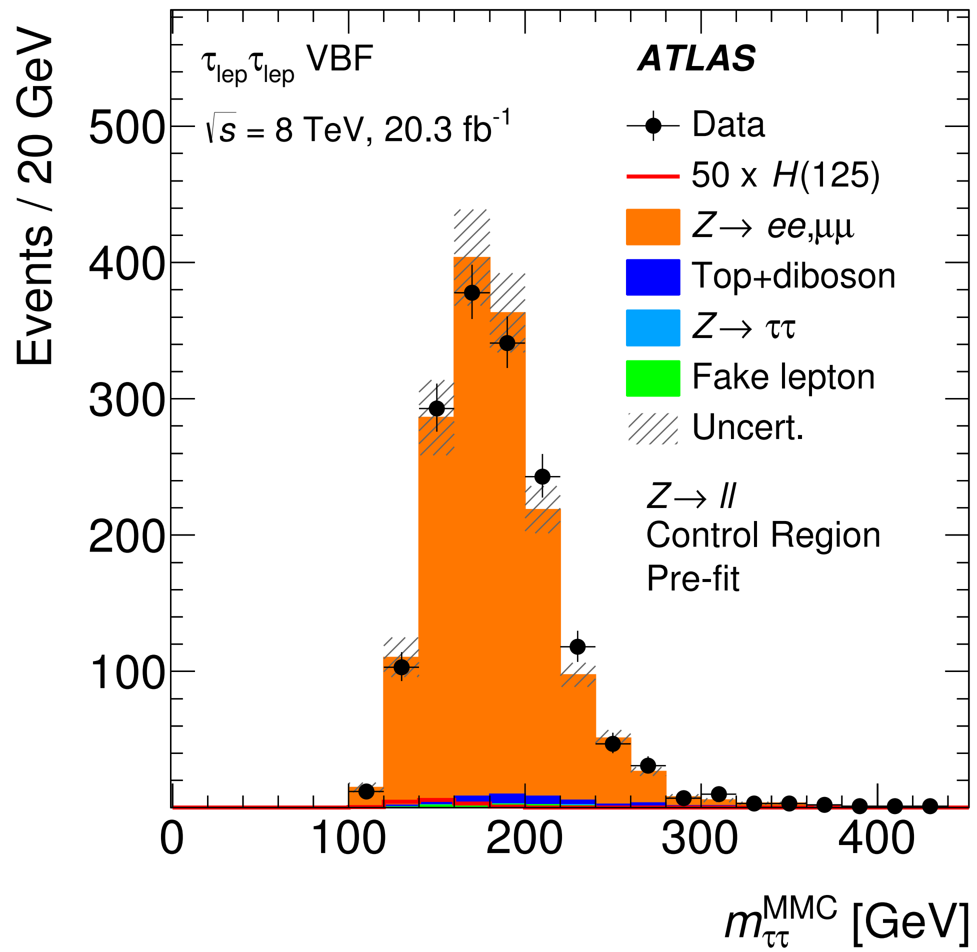
where η, η_1 and η_2 are the pseudorapidities of the object and the two leading jets respectively. This variable has a value of 1 when the object is halfway in η between the two jets, 1/e when the object is aligned with one of the jets, and $< 1/\mathrm{e}$ when the object is not between the jets in η. In the $\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$ channel the η centrality of a third jet in the event, $C_{\eta_1,\eta_2}(\eta_{j_3})$, and the product of the η centralities of the two leptons are used as BDT input variables, while in the $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channel the η centrality of the lepton, $C_{\eta_1,\eta_2}(\eta_\ell)$, is used, and in the $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channel the η centrality of each τ, $C_{\eta_1,\eta_2}(\eta_{\tau_1})$ and $C_{\eta_1,\eta_2}(\eta_{\tau_2})$, is used. Events with only two jets are assigned a dummy value of -0.5 for $C_{\eta_1,\eta_2}(\eta_{j_3})$.

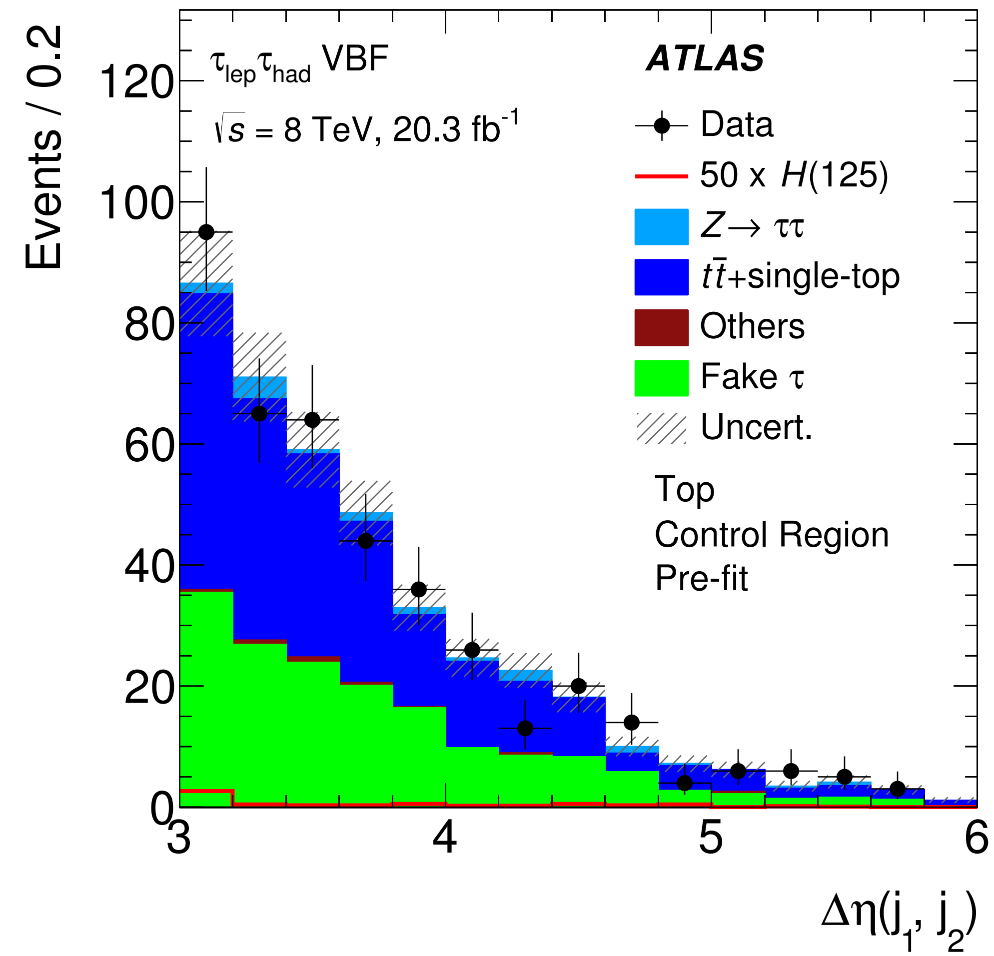
Control Regions

Process	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
$Z \to \ell\ell$-enriched	$80 < m_{\tau\tau}^{\text{vis}} < 100$ GeV (same-flavour)		
Top control region	Invert b-jet veto	Invert b-jet veto and $m_{\text{T}} > 40$ GeV	
Rest category			Pass preselection, Fail VBF and Boosted selections
$Z \to \tau\tau$-enriched	$m_{\tau\tau}^{\text{HPTO}} < 100$ GeV	$m_{\text{T}} < 40$ GeV and $m_{\tau\tau}^{\text{MMC}} < 110$ GeV	
Fake-enriched	Same sign τ decay products	Same sign τ decay products	
W-enriched		$m_{\text{T}} > 70$ GeV	
Mass sideband			$m_{\tau\tau}^{\text{MMC}} < 110$ GeV or $m_{\tau\tau}^{\text{MMC}} > 150$ GeV

Table 6. Summary and definition of the control regions used in the analysis. The requirements shown represent modifications to the signal region requirements. All other selections are applied as for the corresponding signal regions. The variable $m_{\tau\tau}^{\text{HPTO}}$ is the invariant mass of the $\tau\tau$-system obtained using the collinear approximation and the same objects as used in $E_{\text{T}}^{\text{miss,HPTO}}$. Each control region listed is actually two control regions, corresponding to the VBF or boosted categories, with the exception of the rest category. The first three control regions listed are used in the global fit defined in section 8.

lep-lep Control Regions





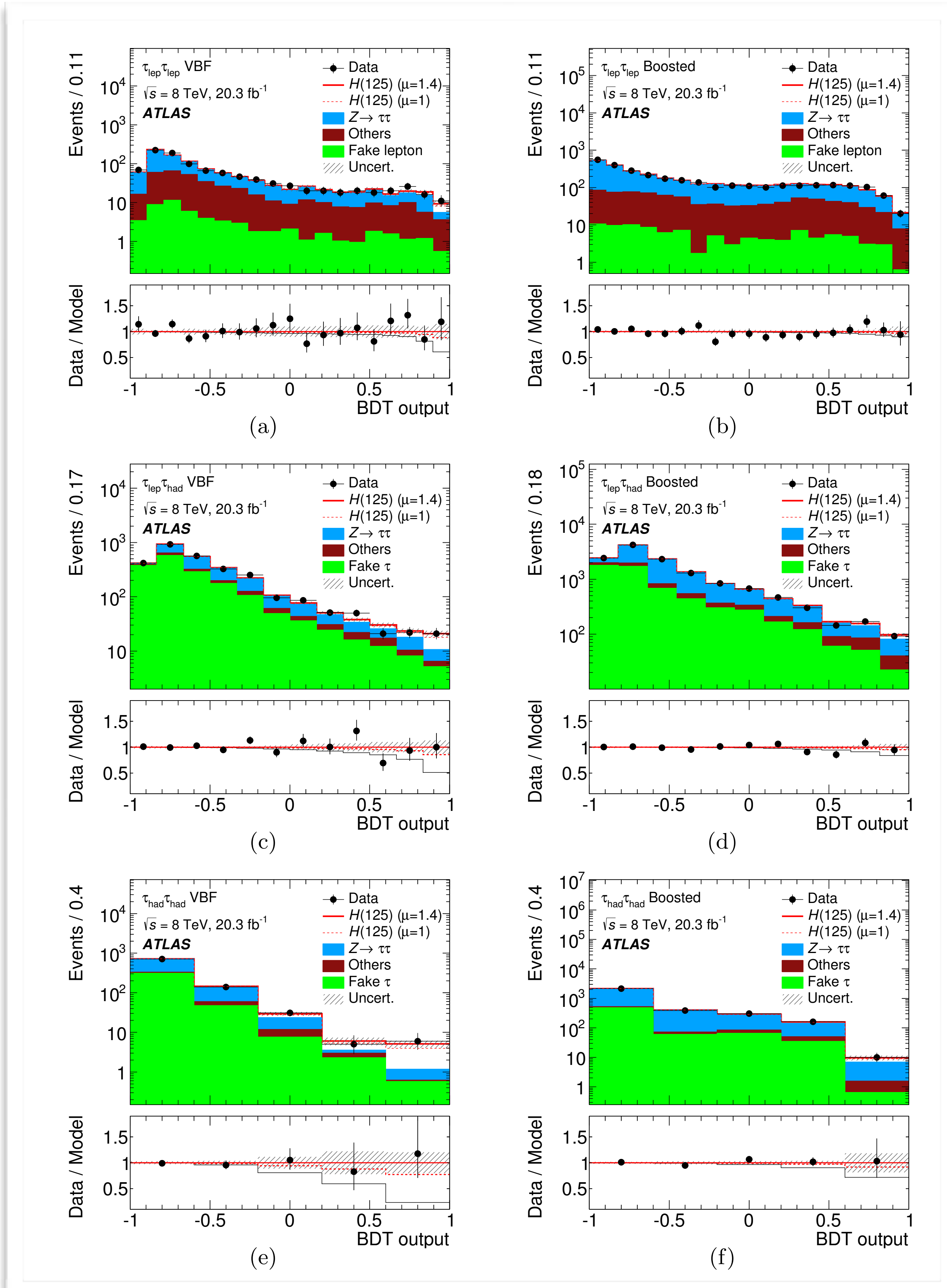
Background Scale Factors

Channel	Background	Scale factors (CR) VBF	Boosted
$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	Top	0.99 ± 0.07	1.01 ± 0.05
	$Z \to ee$	0.91 ± 0.16	0.98 ± 0.10
	$Z \to \mu\mu$	0.97 ± 0.13	0.96 ± 0.08
$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	Top	0.84 ± 0.08	0.96 ± 0.04

Systematics

Source	Relative signal and background variations [%]											
	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$ VBF		$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$ Boosted		$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ VBF		$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ Boosted		$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ VBF		$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ Boosted	
	S	B	S	B	S	B	S	B	S	B	S	B
Experimental												
Luminosity	± 2.8	± 0.1	± 2.8	± 0.1	± 2.8	± 0.1	± 2.8	± 0.1	± 2.8	± 0.1	± 2.8	± 0.1
Tau trigger*	–	–	–	–	–	–	–	–	$^{+7.7}_{-8.8}$	< 0.1	$^{+7.8}_{-8.9}$	< 0.1
Tau identification	–	–	–	–	± 3.3	± 1.2	± 3.3	± 1.8	± 6.6	± 3.8	± 6.6	± 5.1
Lepton ident. and trigger*	$^{+1.4}_{-2.1}$	$^{+1.3}_{-1.7}$	$^{+1.4}_{-2.1}$	$^{+1.1}_{-1.5}$	± 1.8	± 0.5	± 1.8	± 0.8	–	–	–	–
b-tagging	± 1.3	± 1.6	± 1.6	± 1.6	< 0.1	± 0.2	± 0.4	± 0.2	–	–	–	–
τ energy scale†	–	–	–	–	± 2.4	± 1.3	± 2.4	± 0.9	± 2.9	± 2.5	± 2.9	± 2.5
Jet energy scale and resolution†	$^{+8.5}_{-9.1}$	± 9.2	$^{+4.7}_{-4.9}$	$^{+3.7}_{-3.0}$	$^{+9.5}_{-8.7}$	± 1.0	± 3.9	± 0.4	$^{+10.1}_{-8.0}$	± 0.3	$^{+5.1}_{-6.2}$	± 0.2
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft scale & resolution	$^{+0.0}_{-0.2}$	$^{+0.0}_{-1.2}$	$^{+0.0}_{-0.1}$	$^{+0.0}_{-1.2}$	$^{+0.8}_{-0.3}$	± 0.2	± 0.4	< 0.1	± 0.5	± 0.2	± 0.1	< 0.1
Background Model												
Modelling of fake backgrounds*†	–	± 1.2	–	± 1.2	–	± 2.6	–	± 2.6	–	± 5.2	–	± 0.6
Embedding†	–	$^{+3.8}_{-4.3}$	–	$^{+6.0}_{-6.5}$	–	± 1.5	–	± 1.2	–	± 2.2	–	± 3.3
$Z \to \ell\ell$ normalisation*	–	± 2.1	–	± 0.7	–	–	–	–	–	–	–	–
Theoretical												
Higher-order QCD corrections †	$^{+11.3}_{-9.1}$	± 0.2	$^{+19.8}_{-15.3}$	± 0.2	$^{+9.7}_{-7.6}$	± 0.2	$^{+19.3}_{-14.7}$	± 0.2	$^{+10.7}_{-8.2}$	< 0.1	$^{+20.3}_{-15.4}$	< 0.1
UE/PS	± 1.8	< 0.1	± 5.9	< 0.1	± 3.8	< 0.1	± 2.9	< 0.1	± 4.6	< 0.1	± 3.8	< 0.1
Generator modelling	± 2.3	< 0.1	± 1.2	< 0.1	± 2.7	< 0.1	± 1.3	< 0.1	± 2.4	< 0.1	± 1.2	< 0.1
EW corrections	± 1.1	< 0.1	± 0.4	< 0.1	± 1.3	< 0.1	± 0.4	< 0.1	± 1.1	< 0.1	± 0.4	< 0.1
PDF †	$^{+4.5}_{-5.8}$	± 0.3	$^{+6.2}_{-8.0}$	± 0.2	$^{+3.9}_{-3.6}$	± 0.2	$^{+6.6}_{-6.1}$	± 0.2	$^{+4.3}_{-4.0}$	± 0.2	$^{+6.3}_{-5.8}$	± 0.1
BR ($H \to \tau\tau$)	± 5.7	–	± 5.7	–	± 5.7	–	± 5.7	–	± 5.7	–	± 5.7	–

Signal Region BDTs



Signal Region Yields

Process/Category	VBF			Boosted		
BDT output bin	All bins	Second to last bin	Last bin	All bins	Second to last bin	Last bin
$Z \to \tau\tau$	589 ± 24	9.7 ± 1.0	1.99 ± 0.34	2190 ± 80	33.7 ± 2.3	11.3 ± 1.3
Fake background	57 ± 12	1.2 ± 0.6	0.55 ± 0.35	100 ± 40	2.9 ± 1.3	0.6 ± 0.4
Top	131 ± 19	0.9 ± 0.4	0.89 ± 0.33	380 ± 50	9.8 ± 2.1	4.3 ± 1.0
Others	196 ± 17	3.0 ± 0.4	1.7 ± 0.6	400 ± 40	8.3 ± 1.6	2.6 ± 0.7
ggF: $H \to WW$ $(m_H = 125$ GeV)	2.9 ± 0.8	0.12 ± 0.04	0.11 ± 0.04	7.7 ± 2.3	0.43 ± 0.13	0.24 ± 0.08
VBF: $H \to WW$	3.4 ± 0.4	0.40 ± 0.06	0.38 ± 0.08	1.65 ± 0.18	0.102 ± 0.017	< 0.1
$WH: H \to WW$	< 0.1	< 0.1	< 0.1	0.90 ± 0.10	< 0.1	< 0.1
$ZH: H \to WW$	< 0.1	< 0.1	< 0.1	0.59 ± 0.07	< 0.1	< 0.1
ggF: $H \to \tau\tau$ $(m_H = 125\,\mathrm{GeV})$	9.8 ± 3.4	0.73 ± 0.26	0.35 ± 0.14	21 ± 8	2.4 ± 0.9	1.3 ± 0.5
VBF: $H \to \tau\tau$	13.3 ± 4.0	2.7 ± 0.7	3.3 ± 0.9	5.5 ± 1.5	0.95 ± 0.26	0.49 ± 0.13
$WH: H \to \tau\tau$	0.25 ± 0.07	< 0.1	< 0.1	3.8 ± 1.0	0.44 ± 0.12	0.22 ± 0.06
$ZH: H \to \tau\tau$	0.14 ± 0.04	< 0.1	< 0.1	2.0 ± 0.5	0.21 ± 0.06	0.113 ± 0.031
Total background	980 ± 22	15.4 ± 1.8	5.6 ± 1.4	3080 ± 50	55 ± 4	19.2 ± 2.1
Total signal	24 ± 6	3.5 ± 0.9	3.6 ± 1.0	33 ± 10	4.0 ± 1.2	2.1 ± 0.6
Data	1014	16	11	3095	61	20

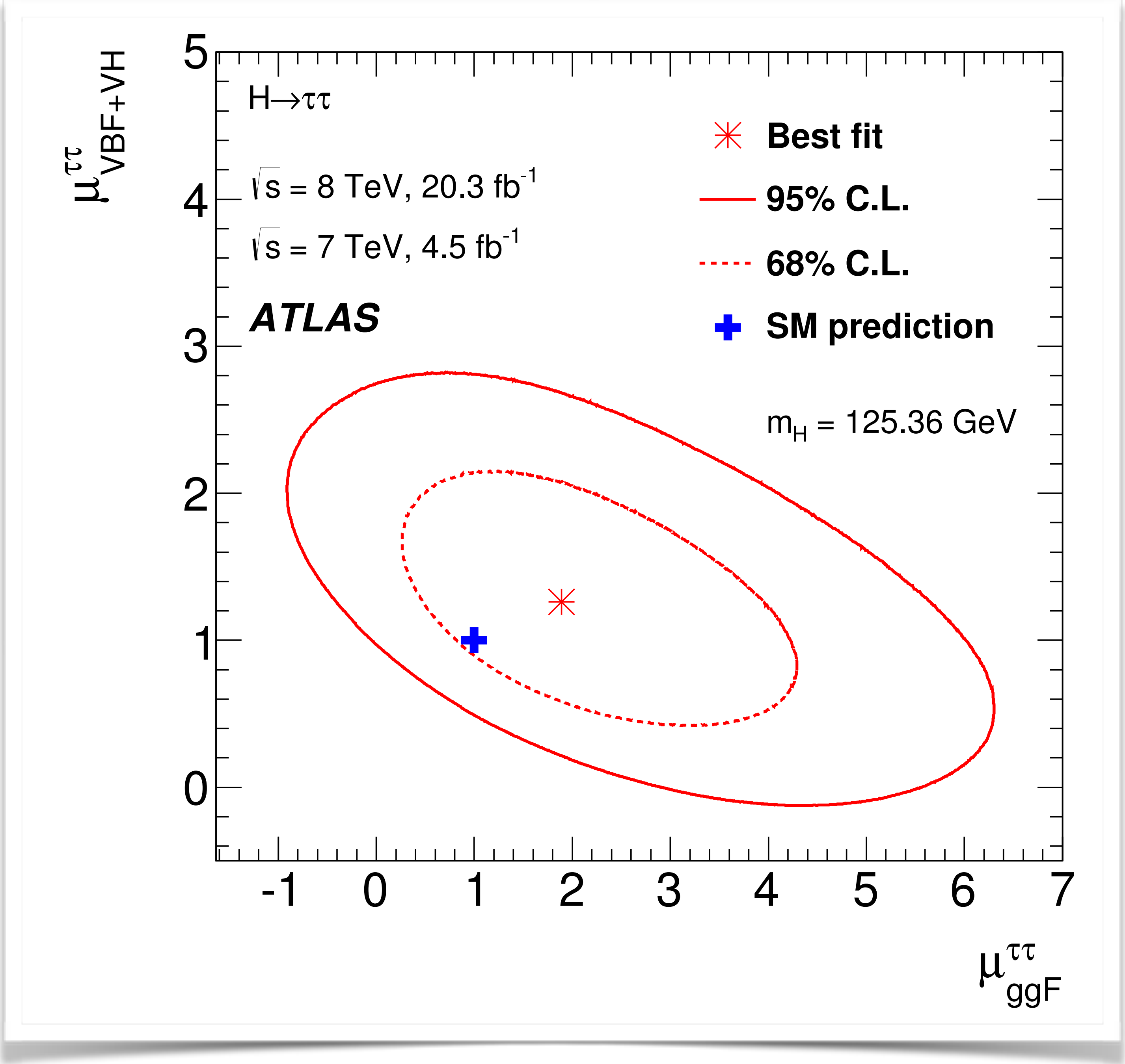
Signal Region Yields

Process/Category	VBF			Boosted		
BDT output bin	All bins	Second to last bin	Last bin	All bins	Second to last bin	Last bin
Fake background	1680 ± 50	8.2 ± 0.9	5.2 ± 0.7	5640 ± 160	51.0 ± 2.5	22.3 ± 1.8
$Z \to \tau\tau$	877 ± 29	7.6 ± 0.9	4.2 ± 0.7	6210 ± 170	57.5 ± 2.8	41.1 ± 3.2
Top	82 ± 15	0.3 ± 0.4	0.5 ± 0.4	380 ± 50	12 ± 4	4.8 ± 1.5
$Z \to \ell\ell(\ell \to \tau_{\mathrm{had}})$	54 ± 26	1.0 ± 0.7	0.30 ± 0.28	200 ± 50	13 ± 4	8.6 ± 3.5
Diboson	63 ± 11	1.0 ± 0.4	0.48 ± 0.20	430 ± 40	9.7 ± 2.2	4.7 ± 1.6
ggF: $H \to \tau\tau$ ($m_H = 125\,\mathrm{GeV}$)	16 ± 6	1.0 ± 0.4	1.2 ± 0.6	60 ± 20	9.2 ± 3.2	10.1 ± 3.4
VBF: $H \to \tau\tau$	31 ± 8	4.5 ± 1.1	9.1 ± 2.2	16 ± 4	2.5 ± 0.6	2.9 ± 0.7
$WH: \ H \to \tau\tau$	0.6 ± 0.4	< 0.1	< 0.1	9.1 ± 2.3	1.3 ± 0.4	1.9 ± 0.5
$ZH: \ H \to \tau\tau$	0.16 ± 0.07	< 0.1	< 0.1	4.6 ± 1.2	0.77 ± 0.20	0.93 ± 0.24
Total background	2760 ± 40	18.1 ± 2.3	10.7 ± 2.7	12860 ± 110	143 ± 6	82 ± 6
Total signal	48 ± 12	5.5 ± 1.3	10.3 ± 2.5	89 ± 26	14 ± 4	16 ± 4
Data	2830	22	21	12952	170	92

Signal Region Yields

Process/Category	VBF			Boosted		
BDT output bin	All bins	Second to last bin	Last bin	All bins	Second to last bin	Last bin
Fake background	370 ± 18	2.3 ± 0.9	0.57 ± 0.29	645 ± 26	35 ± 4	0.65 ± 0.33
Others	37 ± 5	0.67 ± 0.22	< 0.1	89 ± 11	15.9 ± 2.0	0.92 ± 0.22
$Z \to \tau\tau$	475 ± 16	0.6 ± 0.7	0.6 ± 0.4	2230 ± 70	93 ± 4	5.4 ± 1.6
ggF: $H \to \tau\tau$ ($m_H = 125\,\mathrm{GeV}$)	8.0 ± 2.7	0.67 ± 0.23	0.53 ± 0.20	21 ± 8	9.1 ± 3.3	1.6 ± 0.6
VBF: $H \to \tau\tau$	12.0 ± 3.1	1.8 ± 0.5	3.4 ± 0.9	6.3 ± 1.6	2.8 ± 0.7	0.52 ± 0.13
WH : $H \to \tau\tau$	0.25 ± 0.07	< 0.1	< 0.1	4.0 ± 1.1	1.9 ± 0.5	0.41 ± 0.11
ZH : $H \to \tau\tau$	0.16 ± 0.04	< 0.1	< 0.1	2.4 ± 0.6	1.13 ± 0.30	0.23 ± 0.06
Total background	883 ± 18	3.6 ± 1.3	1.2 ± 1.0	2960 ± 50	143 ± 6	7.0 ± 1.8
Total signal	20 ± 5	2.5 ± 0.6	3.9 ± 1.0	34 ± 10	15 ± 4	2.7 ± 0.8
Data	892	5	6	3020	161	10

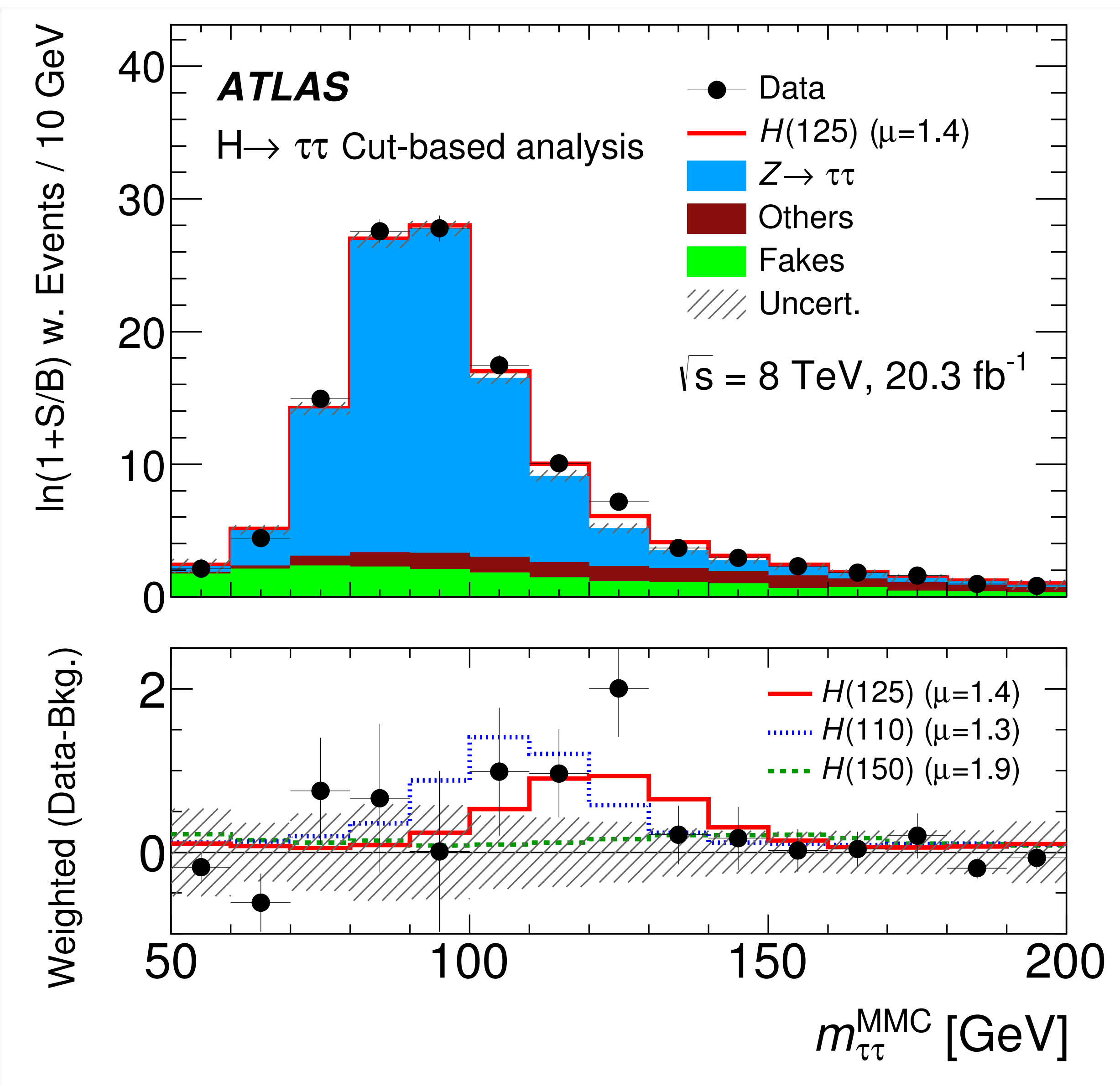
ggF vs VBF/VH


H→ττ
√s = 8 TeV, 20.3 fb-1
√s = 7 TeV, 4.5 fb-1
ATLAS
Best fit
95% C.L.
68% C.L.
SM prediction
mH = 125.36 GeV
μττ VBF+VH
μττ ggF
5
4
3
2
1
0
-1
0
1
2
3
4
5
6
7

Cross-section

	Measured $\sigma\times$BR [pb]	Predicted $\sigma\times$BR [pb]
7 TeV	$1.0\ ^{+0.9}_{-0.8}$(stat.)$^{+0.9}_{-0.8}$(syst.)	1.09 ± 0.11
8 TeV	2.1 ± 0.4(stat.)$^{+0.5}_{-0.4}$(syst.)	1.39 ± 0.14
Gluon fusion, 8 TeV	1.7 ± 1.1(stat.)$^{+1.5}_{-1.1}$(syst.)	1.22 ± 0.14
VBF+VH, 8 TeV	0.26 ± 0.09(stat.)$^{+0.06}_{-0.05}$(syst.)	0.17 ± 0.01

Cut-based



	Fitted μ values		
	$\sqrt{s}$	Multivariate analysis	Cut-based analysis
$\tau_{\text{lep}}\tau_{\text{lep}}$	8 TeV	$1.9^{+1.0}_{-0.9}$	$3.2^{+1.4}_{-1.3}$
$\tau_{\text{lep}}\tau_{\text{had}}$	8 TeV	$1.1^{+0.6}_{-0.5}$	$0.7^{+0.7}_{-0.6}$
$\tau_{\text{had}}\tau_{\text{had}}$	8 TeV	$1.8^{+0.9}_{-0.7}$	$1.6^{+0.9}_{-0.7}$
All channels	8 TeV	$1.53^{+0.47}_{-0.41}$	$1.43^{+0.55}_{-0.49}$