BEAUTY 2019

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FCNC in top quark transitions in ATLAS

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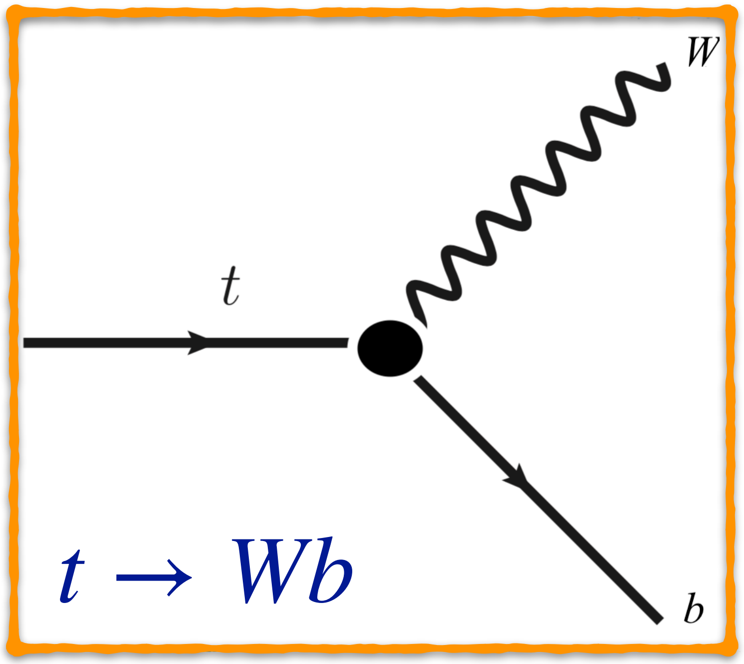
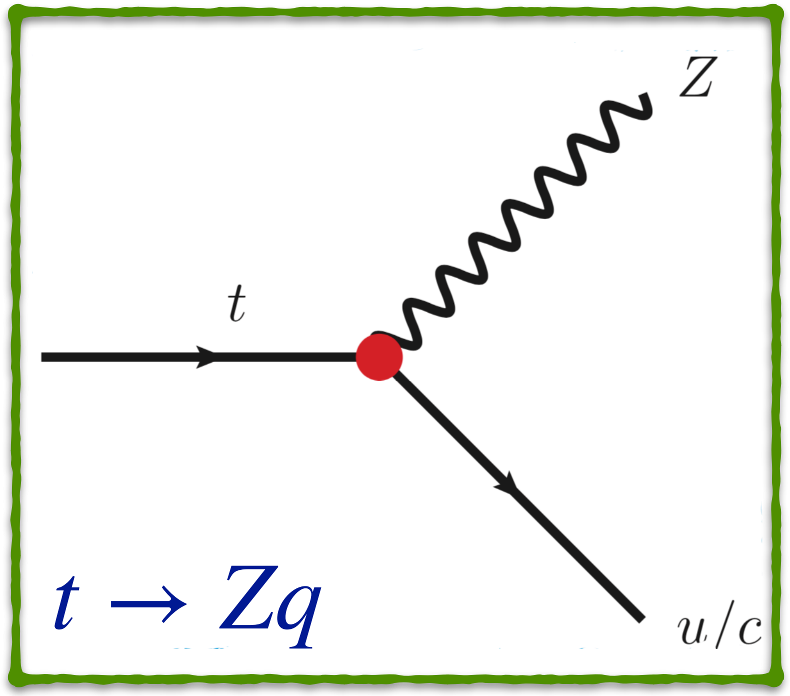
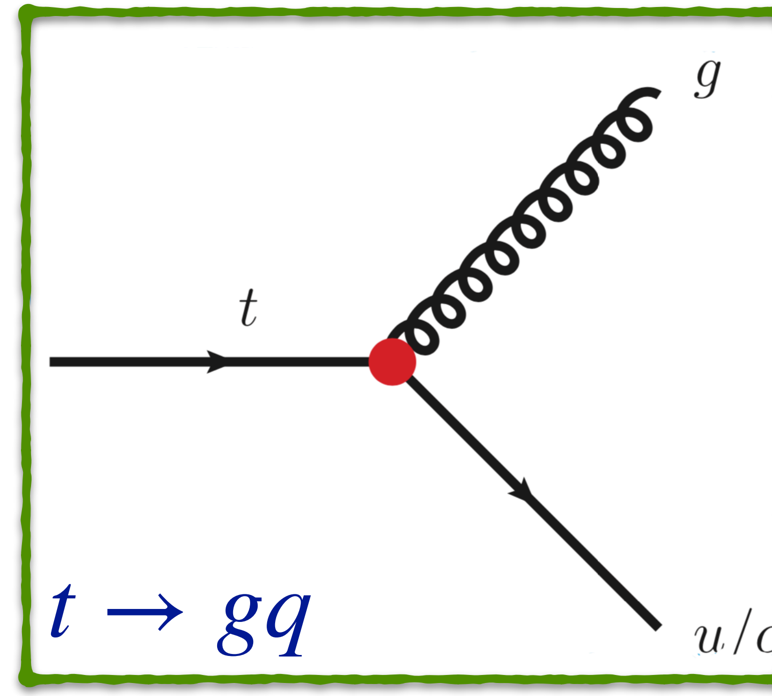
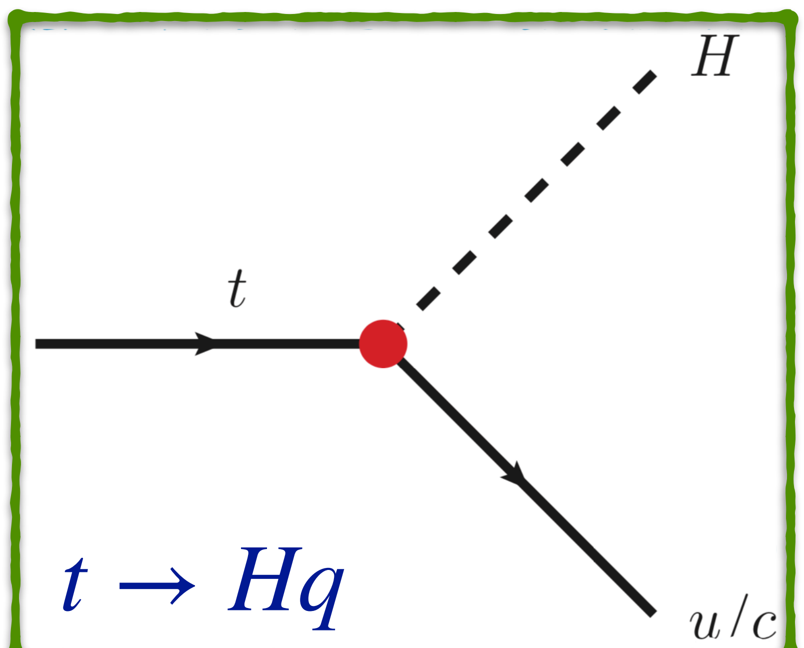
FCNC couplings

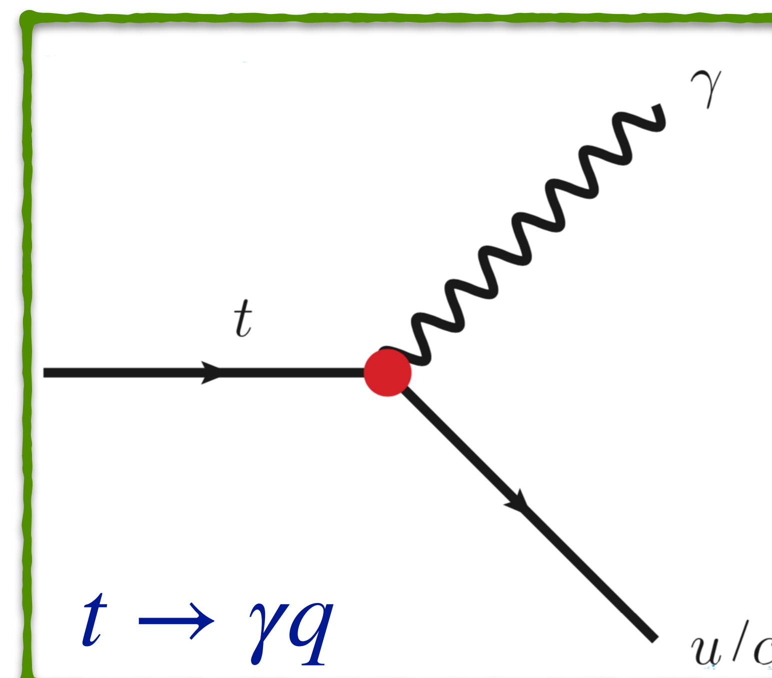
Dominant **SM** top coupling







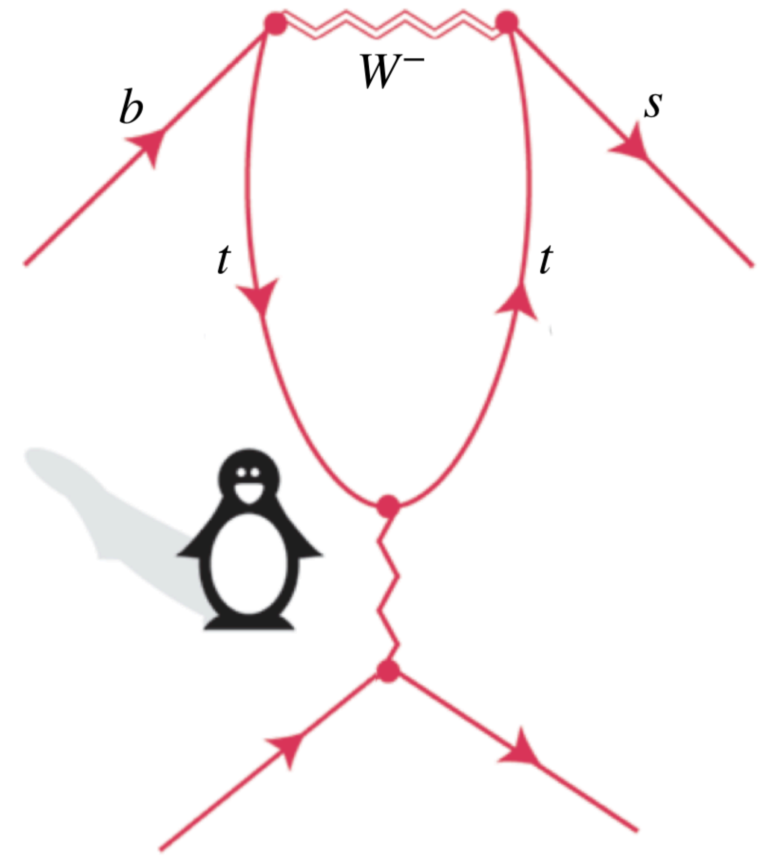




$t\bar{t}$ production

single top production

Flavour **C**hanging **N**eutral **C**urrents



SM

→ **forbidden** at **tree level**

→ **one loop** interactions strongly **suppressed** by the **GIM** mechanism (negligible $\mathscr{B}$)

BSM

→ **increase rates** several orders depending on the model

↪ quark singlets (**QS**), two Higgs doublet (**2HDM**) with and without flavour conservation (**FC**), supersymmetric extensions of the SM (**MSSM**, **$\not{R}$ SUSY**)

	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	–	–	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	–	–	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	–	–	8×10^{-5}	2×10^{-4}
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	–	10^{-5}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

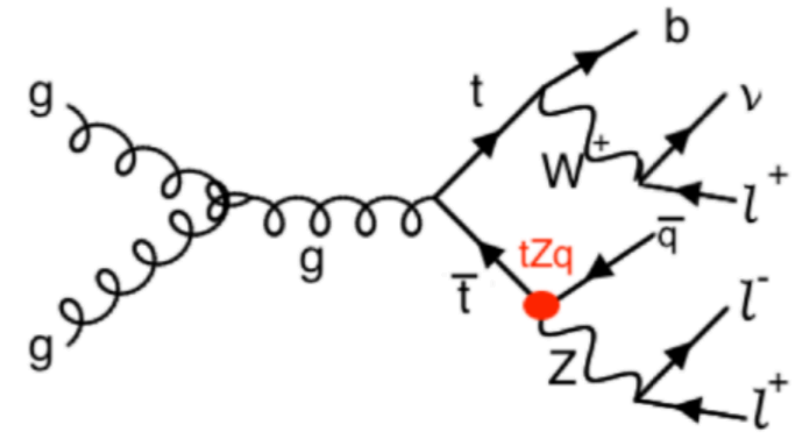
arXiv:hep-ph/0409342

$t \to Zq$

$t\bar{t}$ production
@13TeV
$\mathscr{L} = 36.1\text{fb}^{-1}$

Signature

- 3 isolated charged **leptons** (e, μ) → 2 with $m_{\ell\ell}$ close to Z mass
- $\geq$ 2 **jets** (= 1 **b-tagged)**
- $\not{E}_T$



Main **backgrounds**: diboson, $t\bar{t}Z$ and tZ

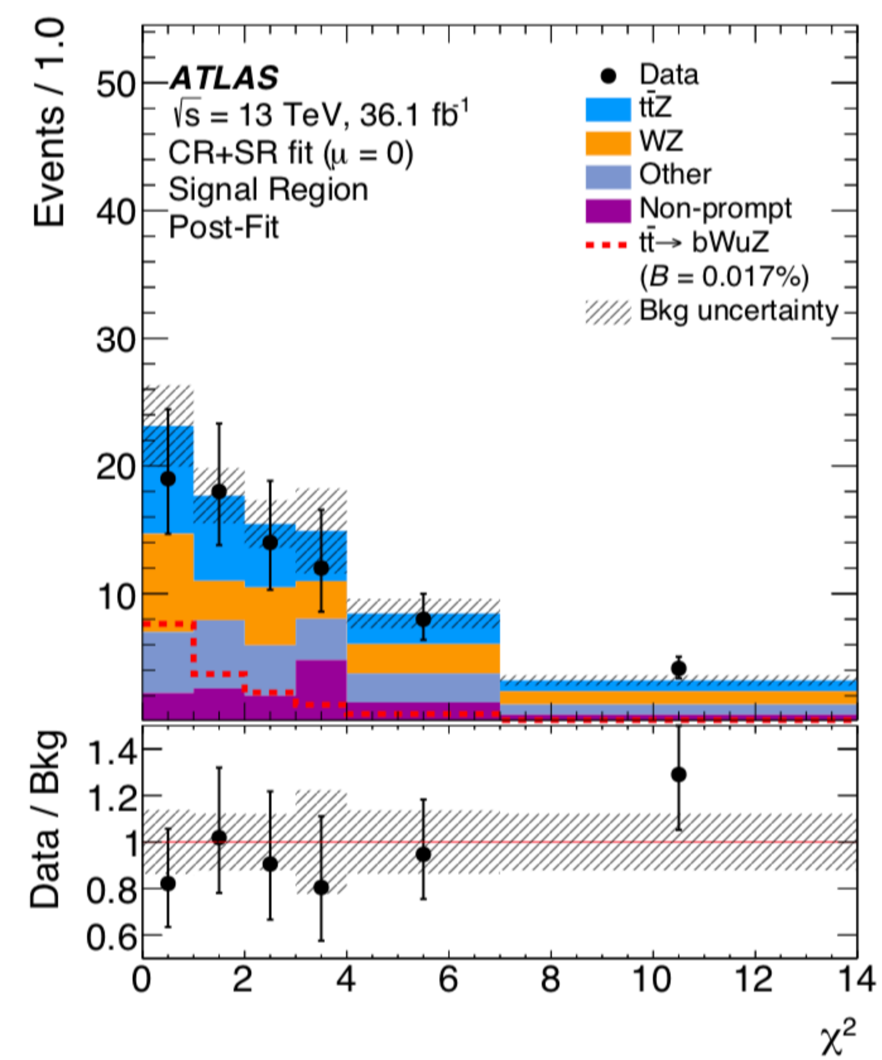
Main **systematic** uncertainties: theoretical normalisation and **background modelling**

Analysis Strategy

↪ event **reconstruction in SR** using a minimized χ^2 variable (to discriminate signal and background) + selection on masses

$$\chi^2 = \frac{\left(m^{\text{reco}}_{j_a\ell_a\ell_b} - m_{t_{\text{FCNC}}}\right)^2}{\sigma^2_{t_{\text{FCNC}}}} + \frac{\left(m^{\text{reco}}_{j_b\ell_c\nu} - m_{t_{\text{SM}}}\right)^2}{\sigma^2_{t_{\text{SM}}}} + \frac{\left(m^{\text{reco}}_{\ell_c\nu} - m_W\right)^2}{\sigma^2_W}$$

↪ binned likelihood **fit** in SR and CR



observed

$$\mathscr{B}(t \to Zu) < 1.7(2.4) \times 10^{-4}$$
$$\mathscr{B}(t \to Zc) < 2.4(3.2) \times 10^{-4}$$

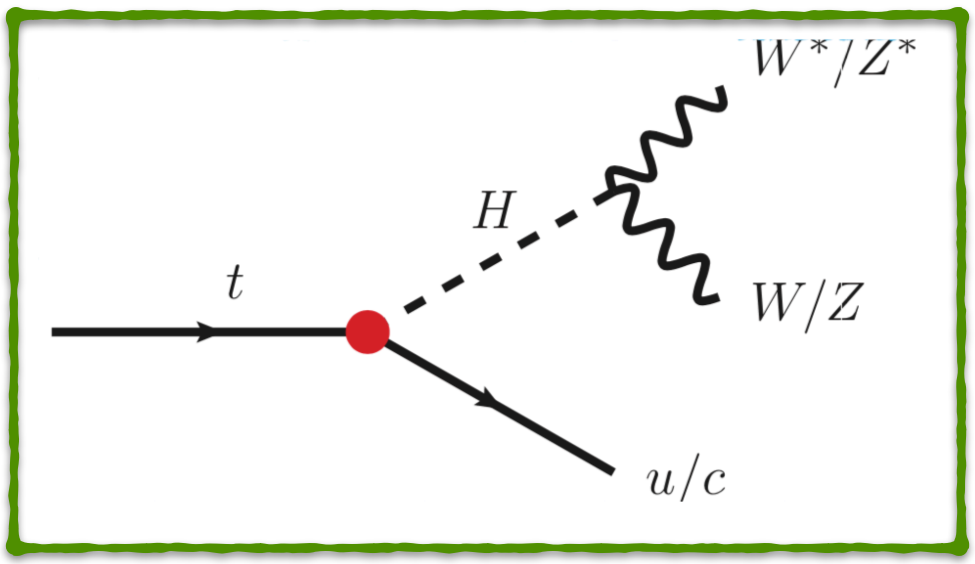
expected

JHEP07(2018)176

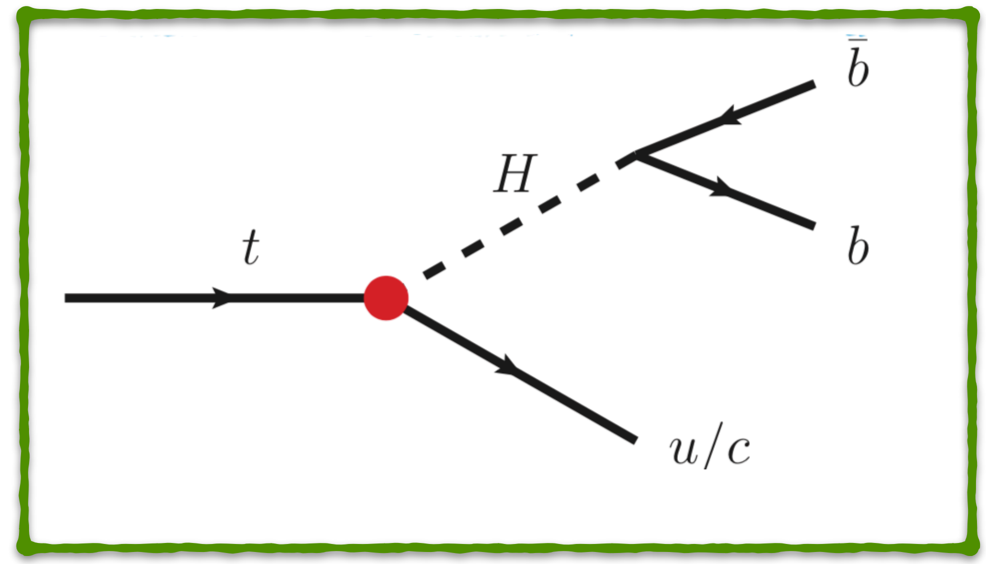
$t \to Hq$

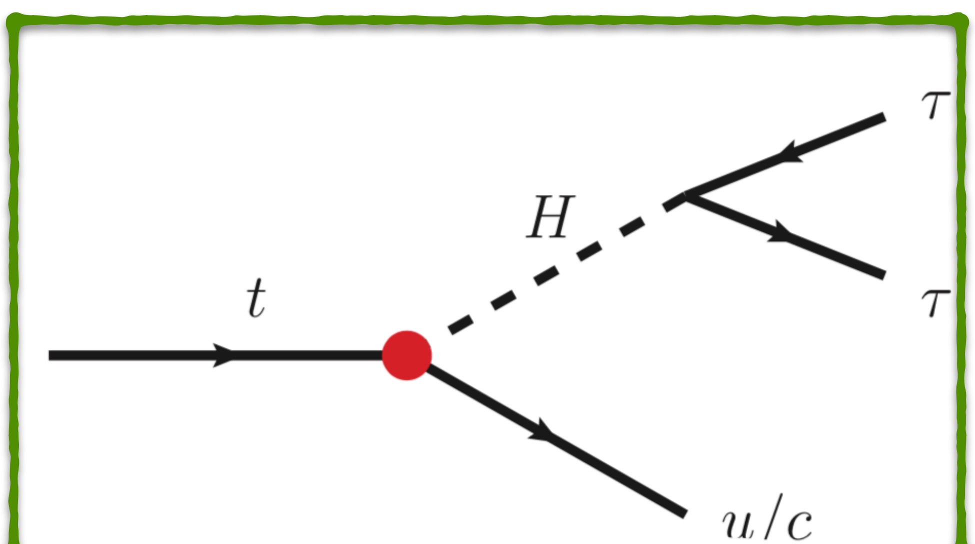
→ **four signatures** accessible depending on the **Higgs** decay
→ dedicated analysis for each signature
→ **combined** interpretation performed by **ATLAS**

$H \to WW^*/ZZ^*$

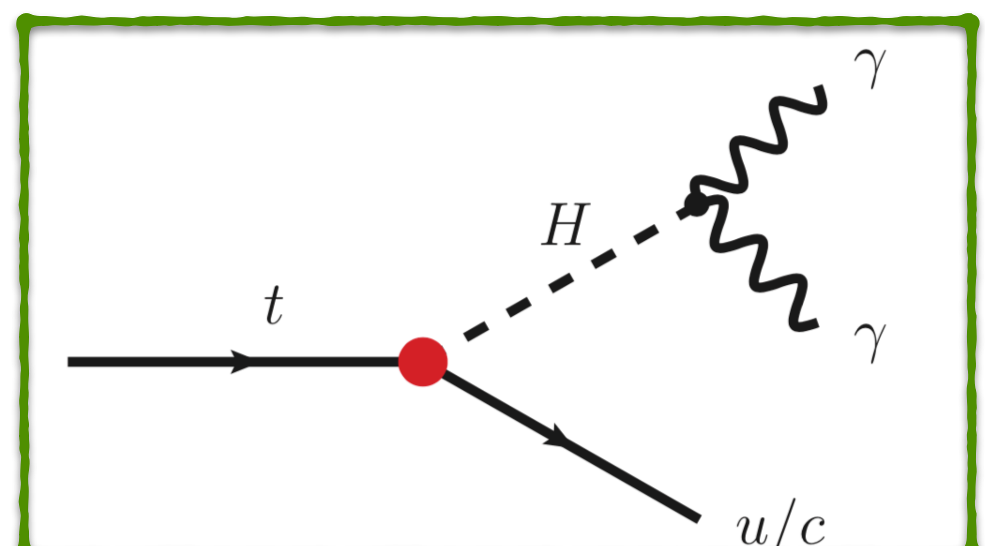


$H \to b\bar{b}$





$H \to \tau\tau$



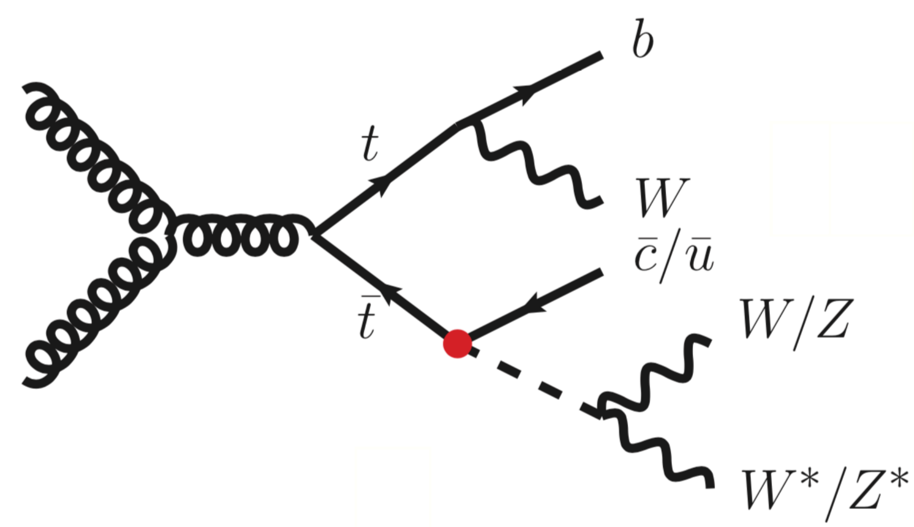
$H \to \gamma\gamma$

$t \to H(WW^*/ZZ^*)q$

$t\bar{t}$ production
@13TeV
$\mathscr{L} = 36.1\text{fb}^{-1}$

Signature → multilepton
2 categories:

- 2 same sign **leptons**, ≥ 4 **jets** (= 1 or 2 **b-tagged**)
- 3 **leptons**, ≥ 2 **jets** (= 1 **b-tagged**)



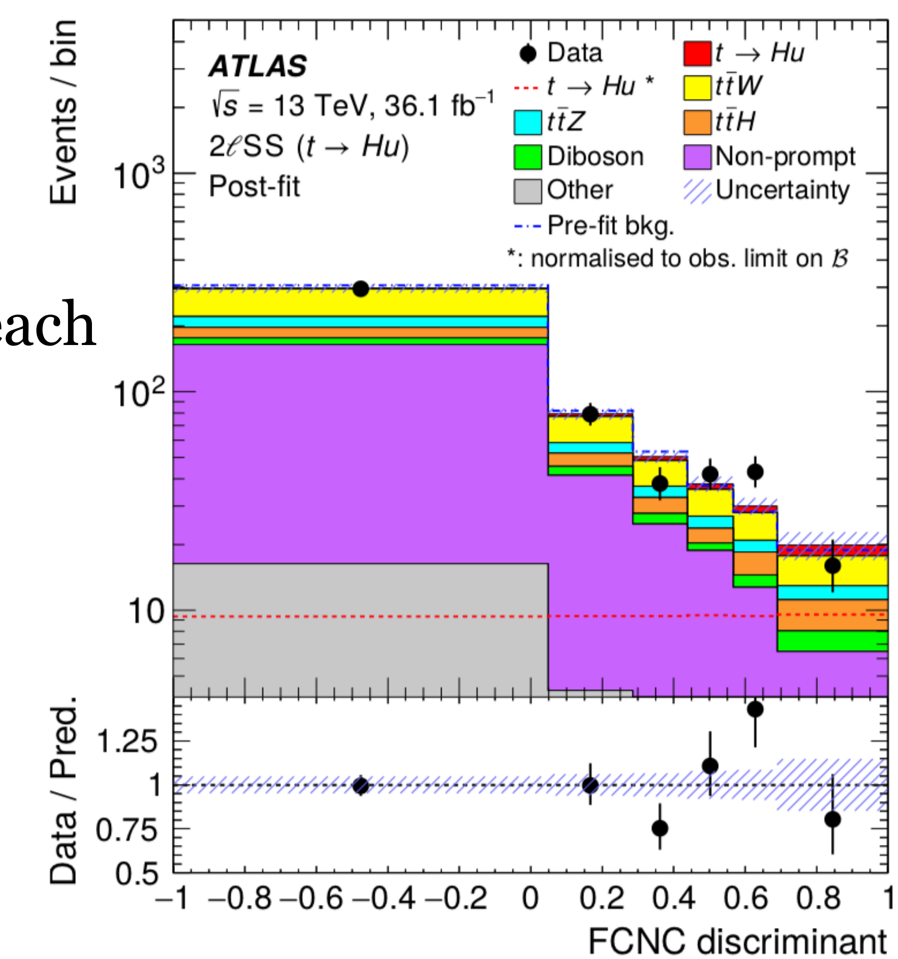
Main **backgrounds**: $t\bar{t}W$ and **non-prompt leptons** (estimated from MC and data)

Main **systematic** uncertainties: **background modelling** + data driven statistical uncertainties

Analysis Strategy

↪ BDTs trained to discriminate signal from background
↪ **2 combined BDTs** (signal vs non-prompt leptons/$t\bar{t}V$) for each category
↪ binned maximum likelihood **fit to BDT** discriminant

$$\mathscr{B}(t \to Hu) < 1.6(1.5) \times 10^{-3}$$
$$\mathscr{B}(t \to Hc) < 1.9(1.5) \times 10^{-3}$$



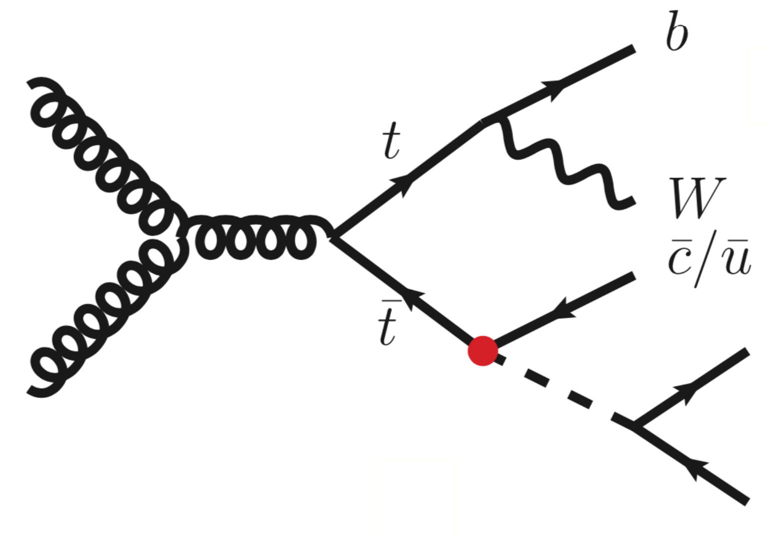
Phys. Rev. D 98 (2018) 032002

Signature

- 1 **lepton** (e or μ)
- ≥ 4 **jets** (≥ 2 **b-tagged**)

$$t \to H(b\bar{b})q$$

$t\bar{t}$ production
@13TeV
$\mathscr{L} = 36.1\text{fb}^{-1}$



Main **background**: $t\bar{t}$ + **HF jets**

Main **systematic** uncertainties: **background modelling** and **c-jet mistagging**

Analysis Strategy

↪ **event categorisation** based on n_{jets} and n_{bjets}

↪ **LH discriminant** based on object kinematics

$$L(\mathbf{x}) = \frac{P^{\text{sig}}(\mathbf{x})}{P^{\text{sig}}(\mathbf{x}) + P^{\text{bkg}}(\mathbf{x})}$$

p.d.f. under the signal hypothesis ($P^{\text{sig}}(\mathbf{x})$)

p.d.f. under the background hypothesis ($P^{\text{bkg}}(\mathbf{x})$)

↪ **binned likelihood fit** under the signal hypothesis

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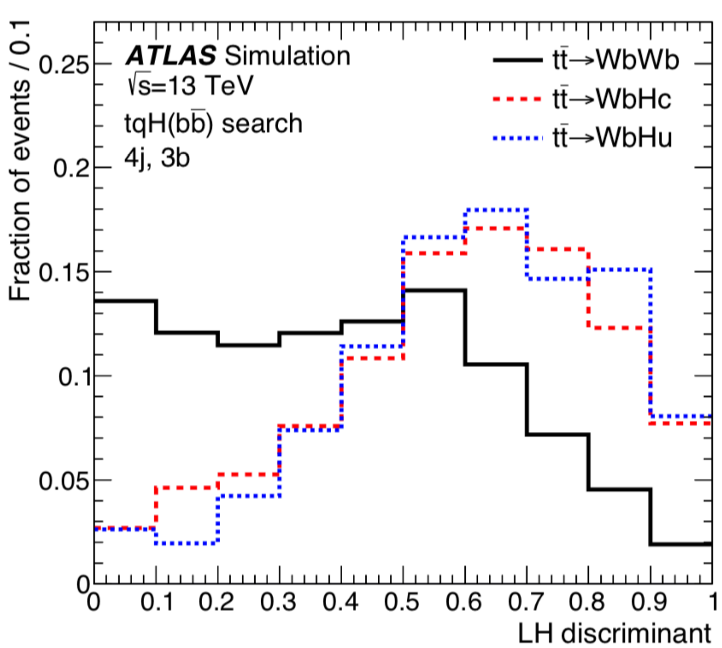
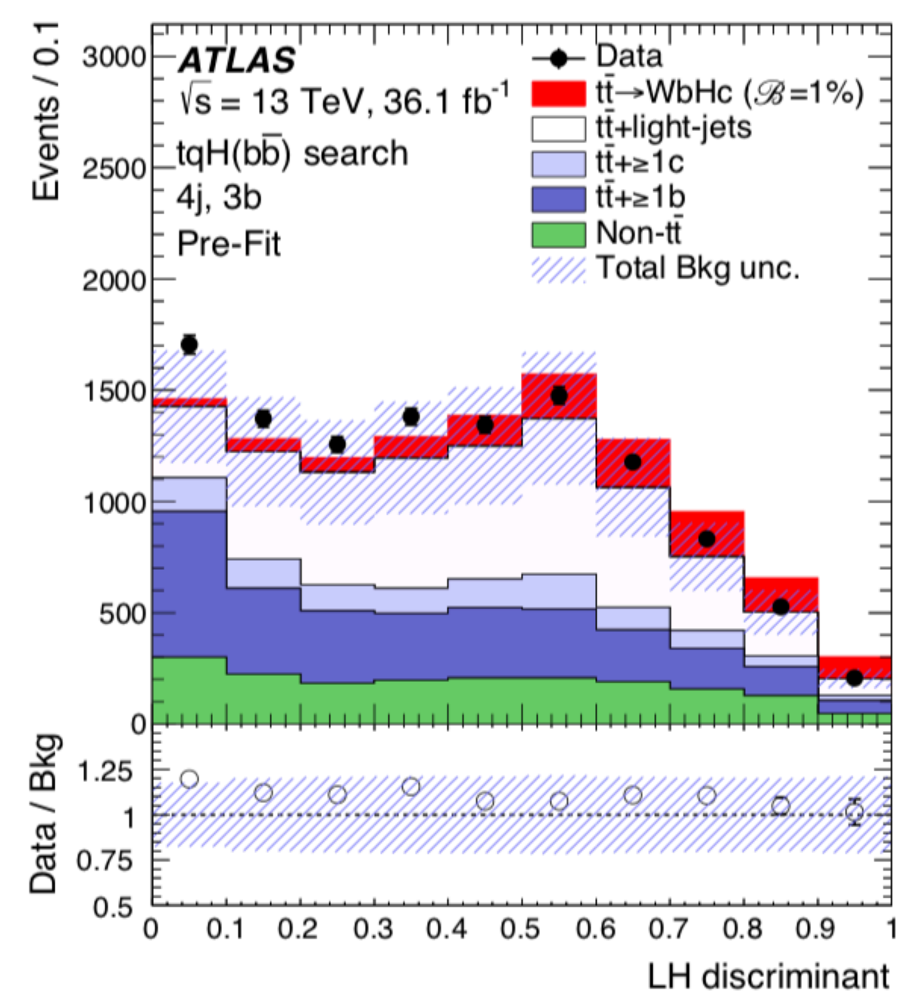


$$\mathscr{B}(t \to Hu) < 5.2(4.9) \times 10^{-3}$$
$$\mathscr{B}(t \to Hc) < 4.2(4.0) \times 10^{-3}$$

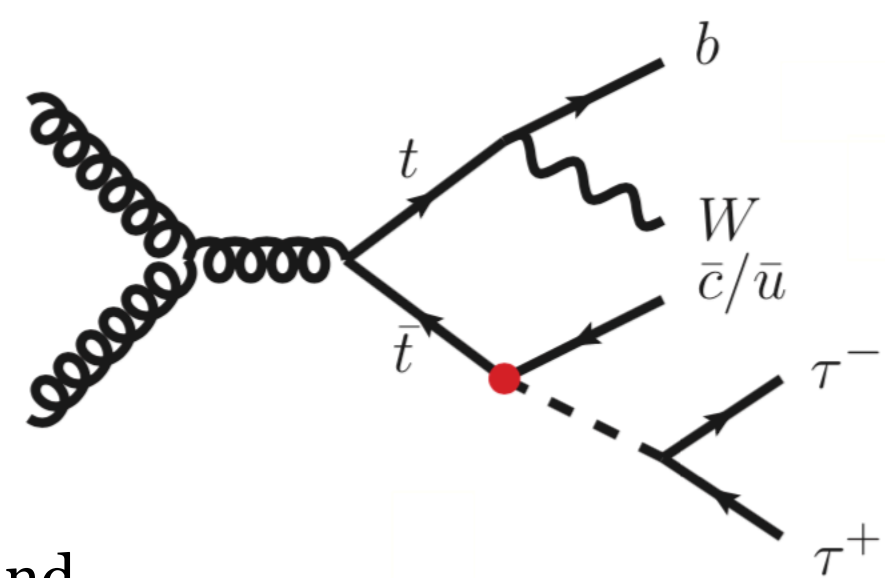


$t \to H(\tau\tau)q$

$t\bar{t}$ production
@13TeV
$\mathscr{L} = 36.1\text{fb}^{-1}$

Signature

- **2τ** (at least one τ_{had})
- multiple **jets**



Main **background**: **fake leptons** (data driven estimation for CR)

Main **systematic** uncertainties: **fake taus** modelling uncertainties

Analysis Strategy

↪ **event categorisation** for SR based on the number of τ_{lep} and τ_{had} and n_{jets}

↪**BDT** with kinematic observables to separate signal from background

↪binned likelihood **fit to BDT** distributions

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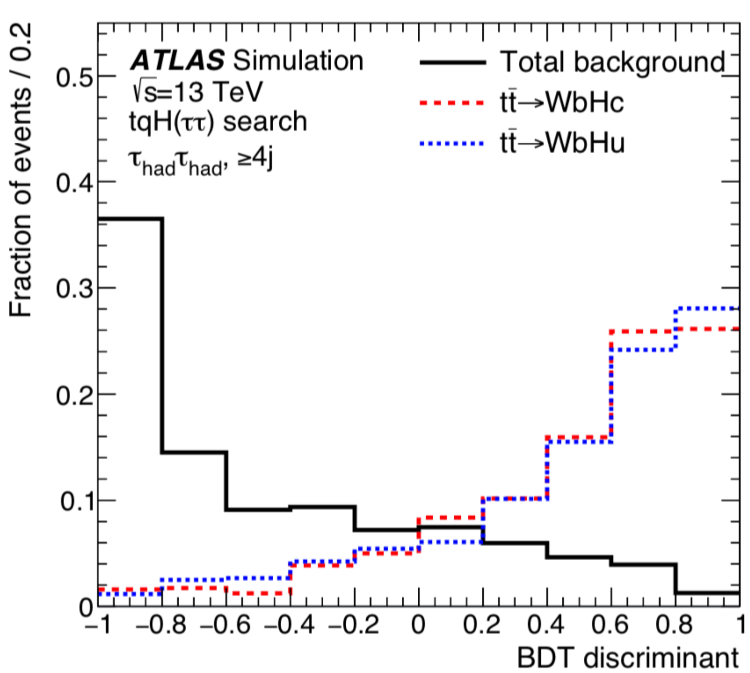
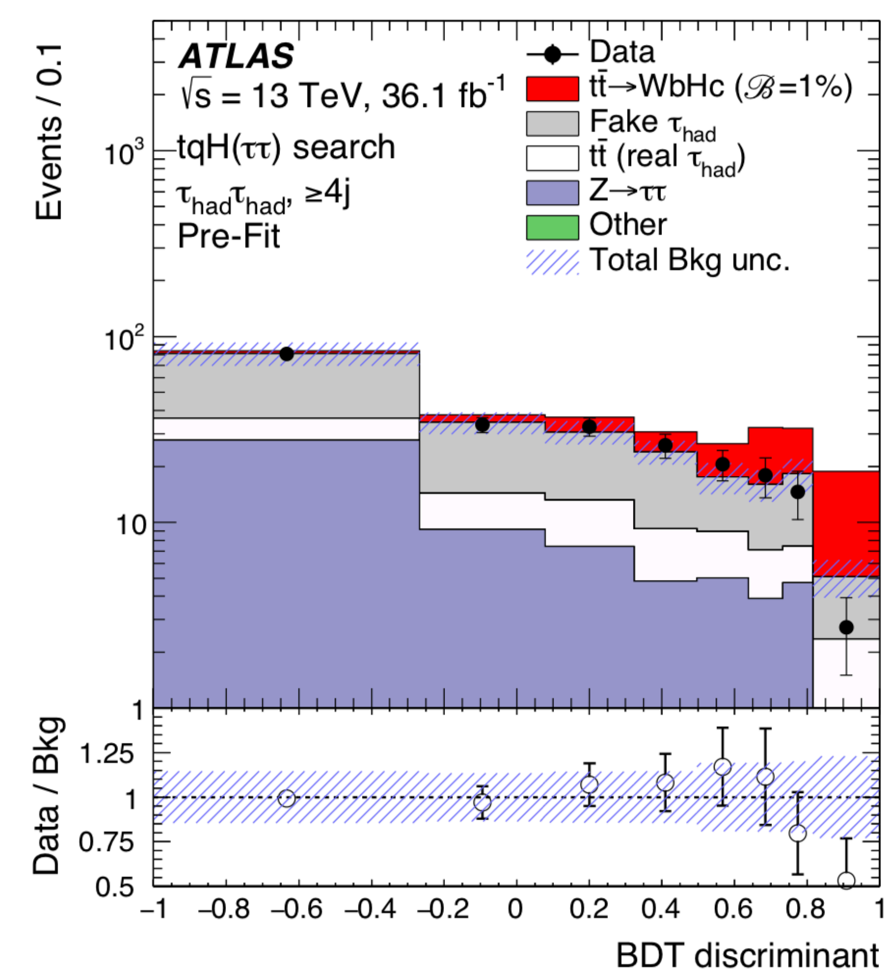


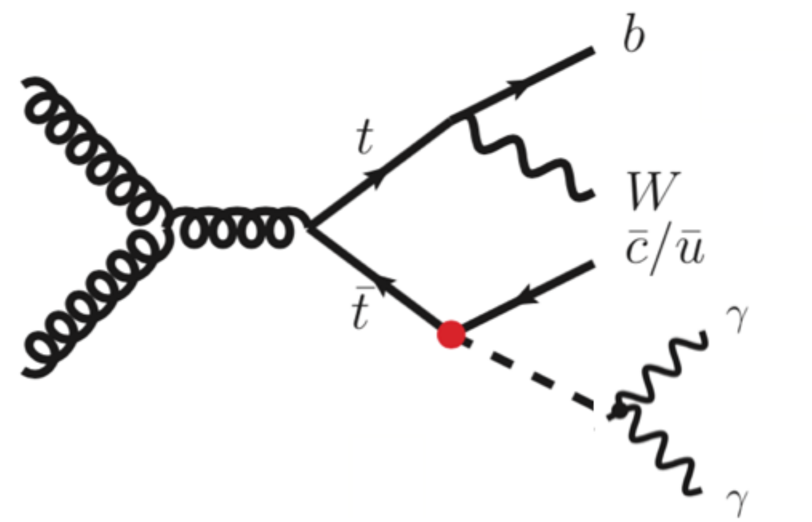
$$\mathscr{B}(t \to Hu) < 1.7(2.0) \times 10^{-3}$$

$$\mathscr{B}(t \to Hc) < 1.9(2.1) \times 10^{-3}$$



$t \to H(\gamma\gamma)q$

$t\bar{t}$ production
@13TeV
$\mathscr{L} = 36.1\text{fb}^{-1}$



Signature → 2γ

1. **hadronic**: ≥ 4 **jets** (≥ 1 **b-tagged**)
2. **leptonic**: 1 **lepton**, ≥ 2 **jets**, $\not\!\!E_T$,

Main **backgrounds**:

1. **hadronic**: $\gamma\gamma$+jets (estimation with fit to data)
2. **leptonic**: $t\bar{t}\gamma$, $W\gamma\gamma$, $\gamma\gamma$+jets (background calibration to data)

Analysis **statistically** limited

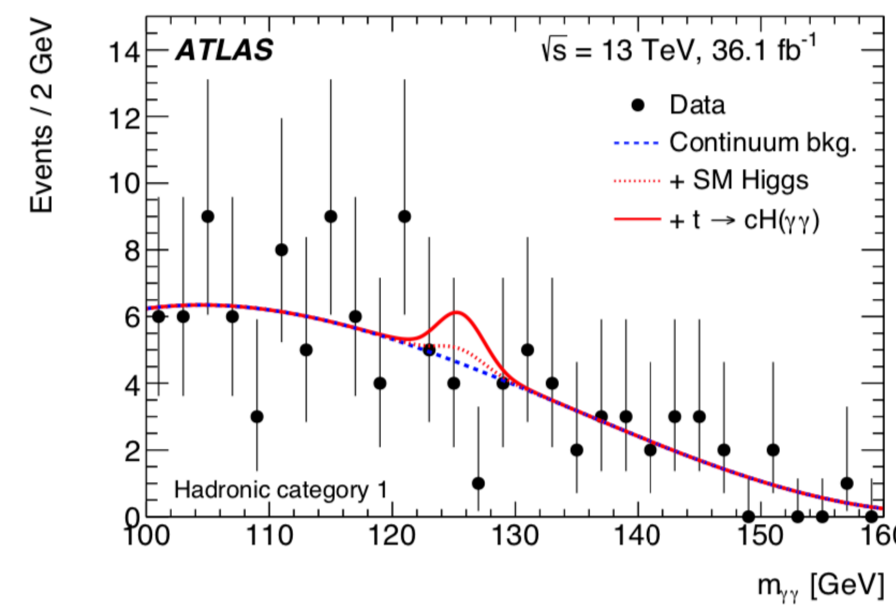
Analysis strategy

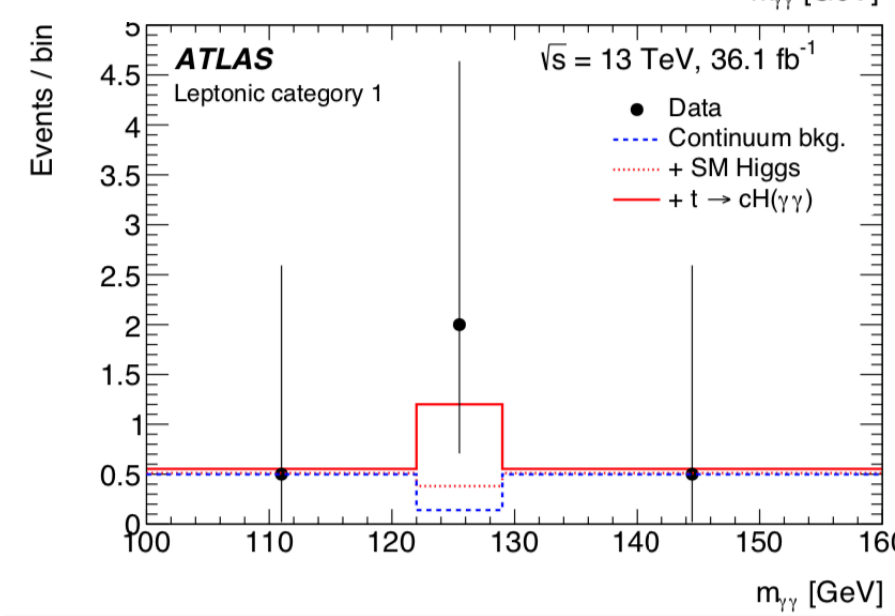
↪ 3-body reconstruction and **mass conditions** on reconstructed tops

↪ **hadronic**: **fit to** $m_{\gamma\gamma}$ spectrum

↪ **leptonic**: **event count**

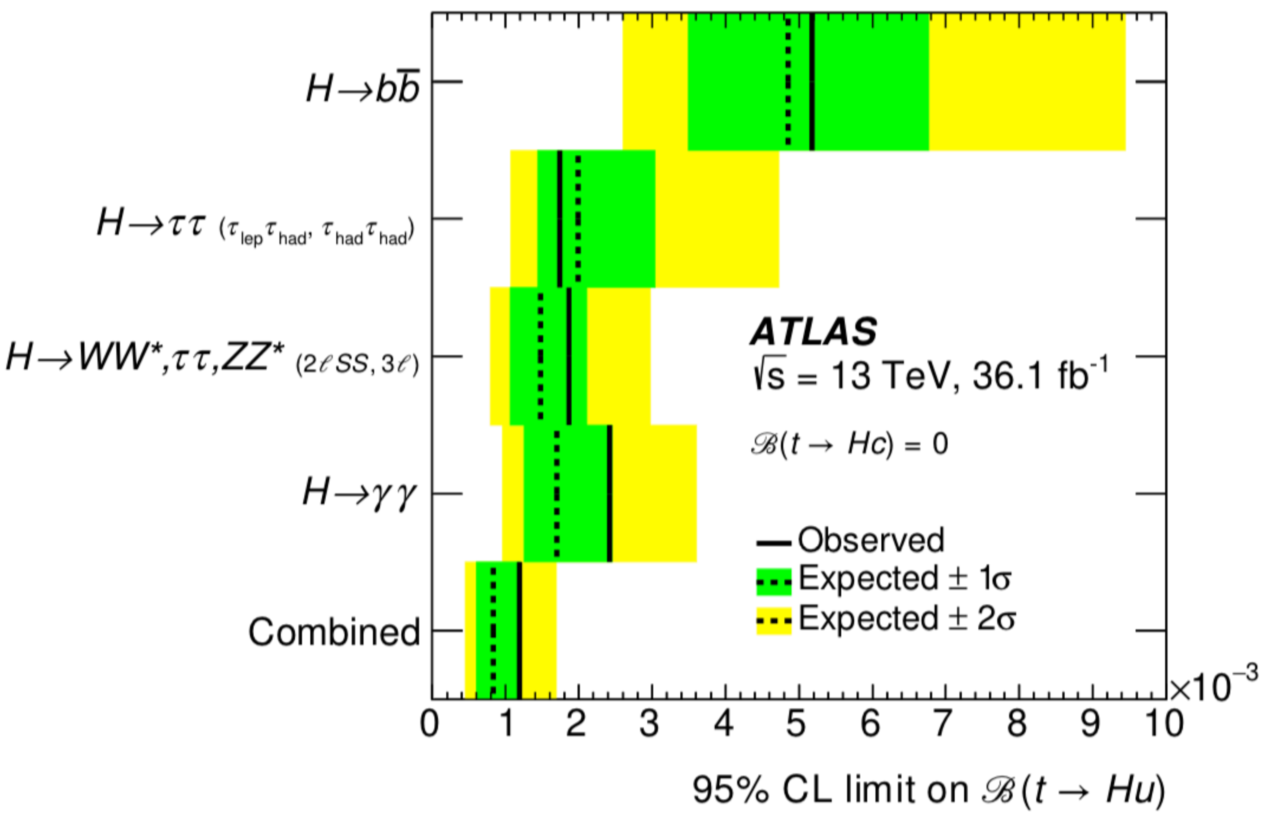
$$\mathscr{B}(t \to Hu) < 1.7(2.4) \times 10^{-3}$$
$$\mathscr{B}(t \to Hc) < 2.2(1.6) \times 10^{-3}$$

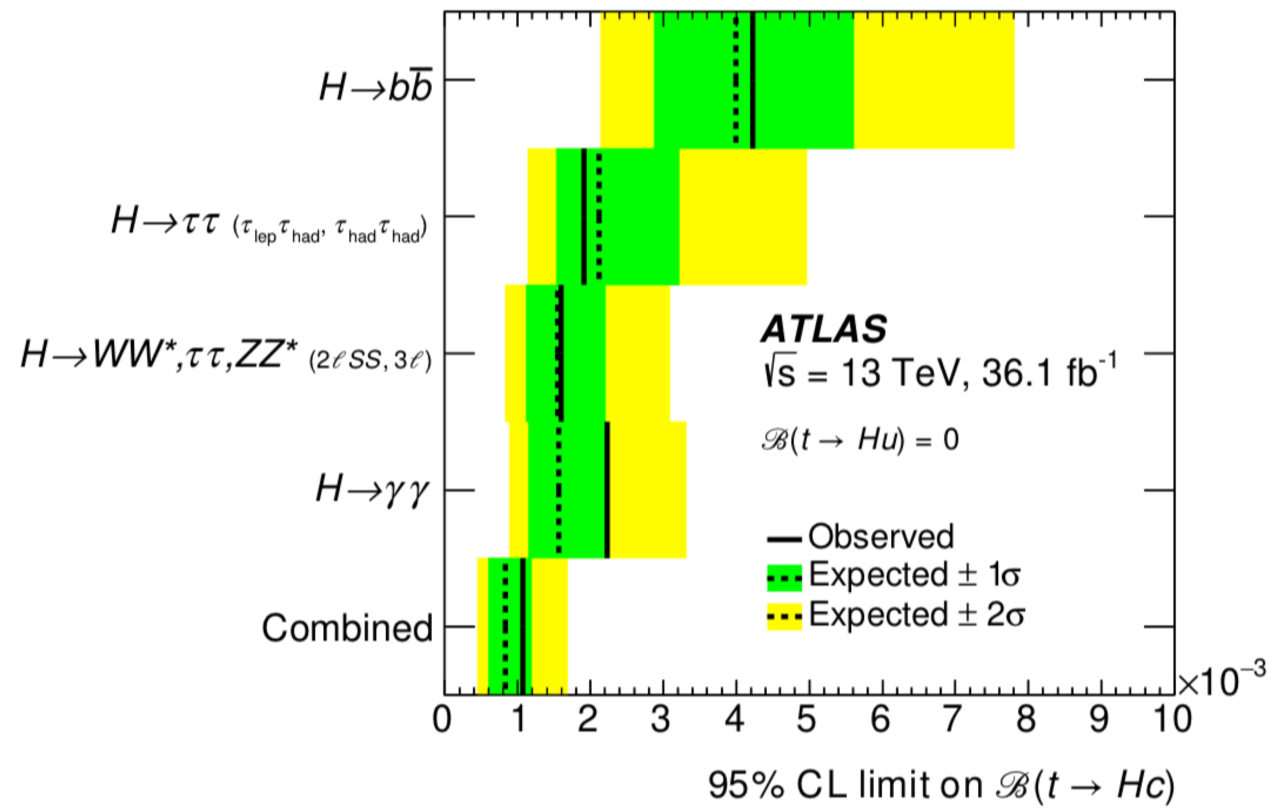




JHEP10(2017)129

$t \to Hq$ Combination





	95% CL upper limits on $\mathcal{B}(t\to Hc)$ Observed (Expected)	95% CL upper limits on $\mathcal{B}(t\to Hu)$ Observed (Expected)
$H\to b\bar{b}$	4.2×10^{-3} (4.0×10^{-3})	5.2×10^{-3} (4.9×10^{-3})
$H\to\tau\tau$ ($\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$)	1.9×10^{-3} (2.1×10^{-3})	1.7×10^{-3} (2.0×10^{-3})
$H\to WW^*, \tau\tau, ZZ^*$ (2ℓSS, 3ℓ)	1.6×10^{-3} (1.5×10^{-3})	1.9×10^{-3} (1.5×10^{-3})
$H\to\gamma\gamma$	2.2×10^{-3} (1.6×10^{-3})	2.4×10^{-3} (1.7×10^{-3})
Combination	1.1×10^{-3} (8.3×10^{-4})	1.2×10^{-3} (8.3×10^{-4})

$$\mathcal{B}(t\to Hu) < 1.2(0.83)\times10^{-3}$$
$$\mathcal{B}(t\to Hc) < 1.1(0.83)\times10^{-3}$$

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$t \to \gamma q$

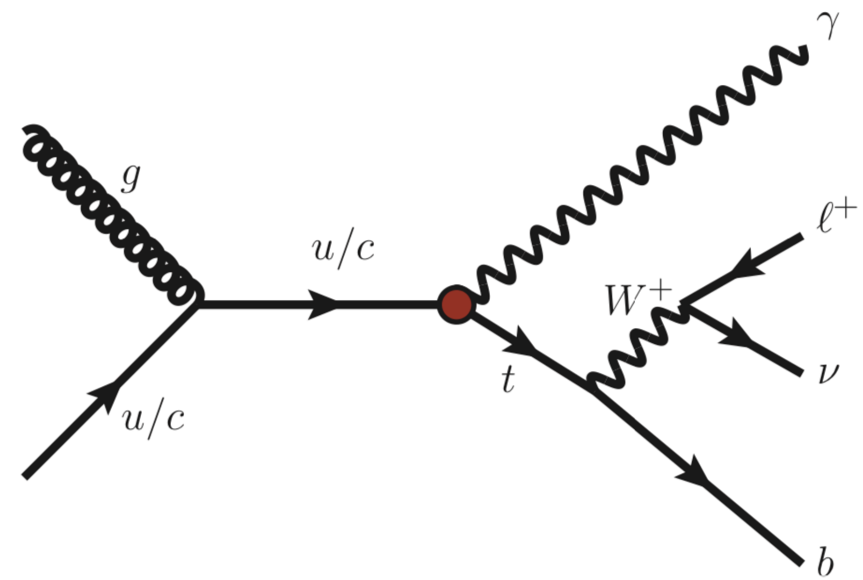
single top production
@13TeV
$\mathscr{L} = 81\text{fb}^{-1}$

Signature

- **SR** $\to 1\gamma$, 1 **lepton** (e or μ), 1 **b-jet**, $\not{E}_T$
- **CR** $\to W + \gamma + \text{jet}, Z + \gamma$

Main **background**:

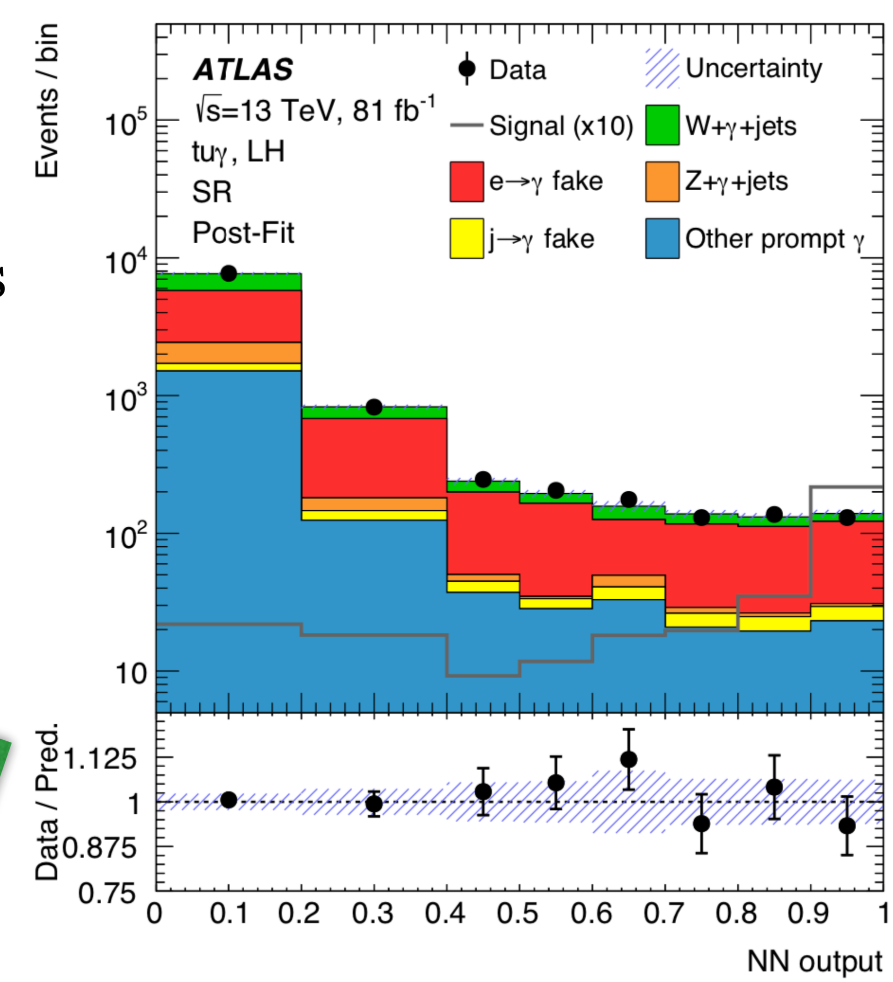
- e **misidentified** as γ ($t\bar{t}$) → data driven estimate
- processes with prompt γ



CERN-EP-2019-155
(Submitted to PLB)

Analysis Strategy

↪ **NN** to discriminate signal from background
↪ binned profile likelihood **fit to NN** output in **SR** and $W + \gamma + \text{jet}$
↪ binned profile likelihood **fit** p_T^γ for $Z + \gamma$
↪ limits derived for **left** (LH) and **right** (RH) handed couplings

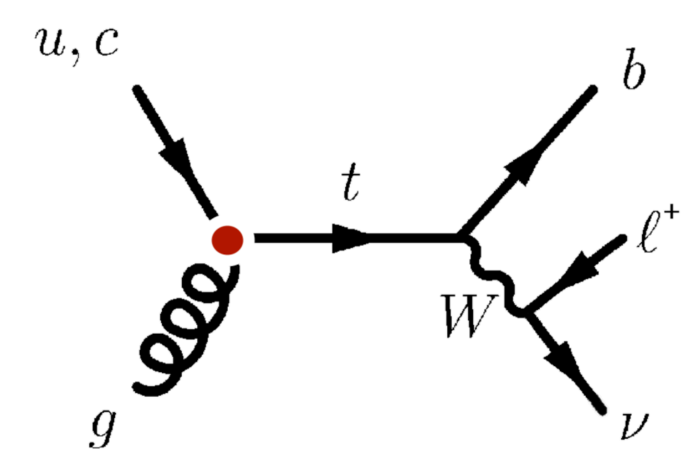


$\mathscr{B}(t \to \gamma u) < 2.8(4.0) \times 10^{-5}$
$\mathscr{B}(t \to \gamma c) < 22(27) \times 10^{-5}$
LH

$\mathscr{B}(t \to \gamma u) < 6.1(5.9) \times 10^{-5}$
$\mathscr{B}(t \to \gamma c) < 18(28) \times 10^{-5}$
RH

$t \to gq$

single top production
@8TeV
$\mathscr{L} = 20.3\text{fb}^{-1}$

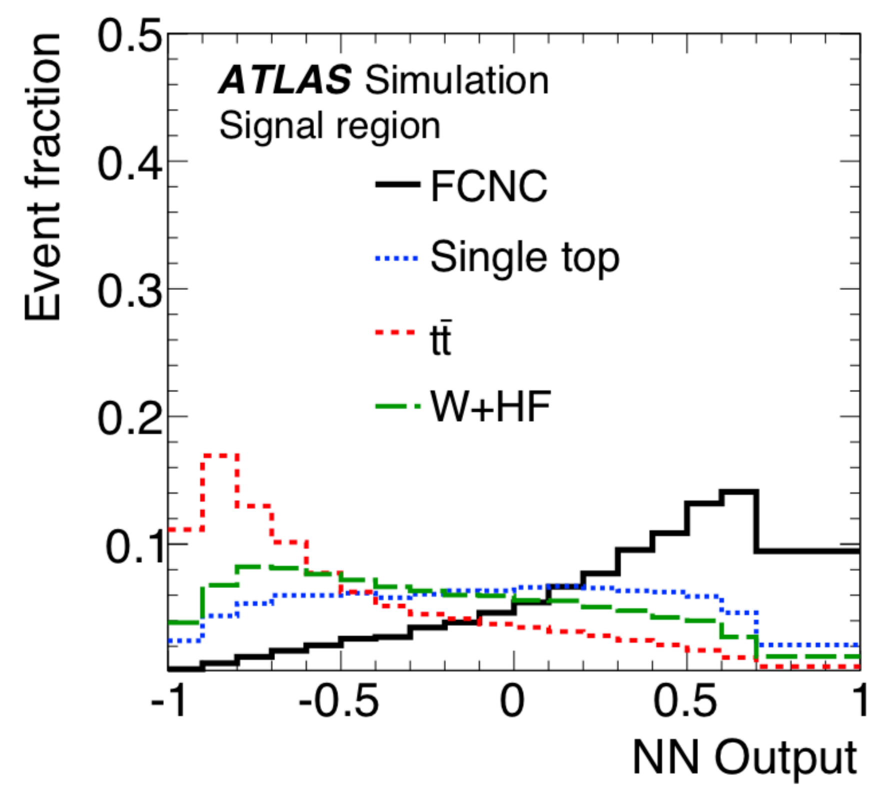


Signature

- 1 isolated **high energy lepton** (e or μ)
- $\not{E}_T$
- 1 jet **b-tagged**

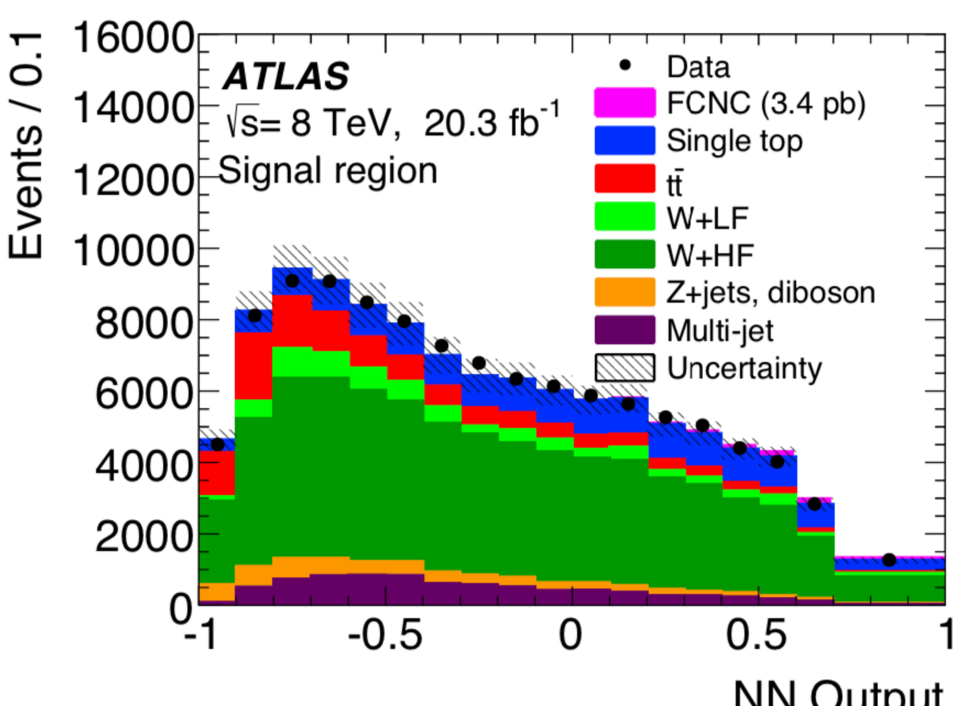
Main **background**: W/Z+jets, $t\bar{t}$, diboson, multijet

Main **systematic** uncertainties: JES, $\not{E}_T$ modelling, normalisation and **modelling of multijet** background



Analysis Strategy

↪ **NN** to discriminate signal and background
↪ binned maximum likelihood **fit to NN output in SR**



$\mathscr{B}(t \to gu) < 0.4(0.35) \times 10^{-4}$
$\mathscr{B}(t \to gc) < 2.0(1.8) \times 10^{-4}$

EPJC 76 (2016) 55

Overview

Strong programme searching for **FCNC** processes in the **top sector**

↪ **several couplings** and final states are investigated

↪ **upper limits** are set on the $\mathscr{B}$

↪ **similar strategy** for all of them: define **SR** and **CR**, use **BDT** or **NN** to discriminate signal and background events, **profile likelihood fit** to these distributions

Next round of analyses with **full 13TeV** dataset

↪ more data

Analysis	Publication date	Reference
$t \to Zq(t\bar{t}@13\text{TeV})$	August 2018	JHEP07(2018)176
$t \to Hq - \text{multilepton}(t\bar{t}@13\text{TeV})$	September 2018	Phys. Rev. D 98 (2018) 032002
$t \to H(\gamma\gamma)q(t\bar{t}@13\text{TeV})$	November 2017	JHEP10(2017)129
$t \to H(b\bar{b}/\tau\tau + \text{combo})(t\bar{t}@13\text{TeV})$	May 2019	JHEP 05 (2019) 123
$t \to \gamma q(\text{SingleTop}@13\text{TeV})$	August 2019	CERN-EP-2019-155 (sub to PLB)
$t \to gq(\text{SingleTop}@8\text{TeV})$	February 2016	EPJC 76 (2016) 55

Thank you for your attention!


BONUS
SLIDES

$t \to Zq$

$t\bar{t} \to WbZ(\ell\ell)q$

Region selection:

Selection	$t\bar{t}Z$ CR	WZ CR	ZZ CR	Non-prompt lepton CR0 (CR1)	SR
No. leptons	3	3	4	3	3
OSSF	Yes	Yes	Yes	Yes	Yes
$\|m_{\ell\ell}^{\text{reco}} - 91.2\text{ GeV}\|$	< 15 GeV	< 15 GeV	< 15 GeV	> 15 GeV	< 15 GeV
No. jets	≥ 4	≥ 2	≥ 1	≥ 2	≥ 2
No. b-tagged jets	2	0	0	0 (1)	1
$E_{\text{T}}^{\text{miss}}$	> 20 GeV	> 40 GeV	> 20 GeV	> 20 GeV	> 20 GeV
$m_{\text{T}}^{\ell\nu}$	-	> 50 GeV	-	-	-
$\|m_{\ell\nu}^{\text{reco}} - 80.4\text{ GeV}\|$	-	-	-	-	< 30 GeV
$\|m_{j\ell\nu}^{\text{reco}} - 172.5\text{ GeV}\|$	-	-	-	-	< 40 GeV
$\|m_{j\ell\ell}^{\text{reco}} - 172.5\text{ GeV}\|$	-	-	-	-	< 40 GeV

Expected number of events:

Sample	Yields	
	Pre-fit	Post-fit
$t\bar{t}Z$	37 ± 5	37 ± 4
WZ	32 ± 19	32 ± 8
ZZ	6.2 ± 3.2	6.4 ± 3.0
Non-prompt leptons	26 ± 11	20 ± 7
Other backgrounds	23 ± 4	23 ± 4
Total background	124 ± 26	119 ± 10
Data	116	116
Data / Bkg	0.94 ± 0.21	0.97 ± 0.12
Signal $t \to uZ$ ($\mathcal{B} = 0.1\%$)	101 ± 8	103 ± 8
Signal $t \to cZ$ ($\mathcal{B} = 0.1\%$)	85 ± 7	87 ± 7

Fitted distributions:

→ χ^2 (SR)

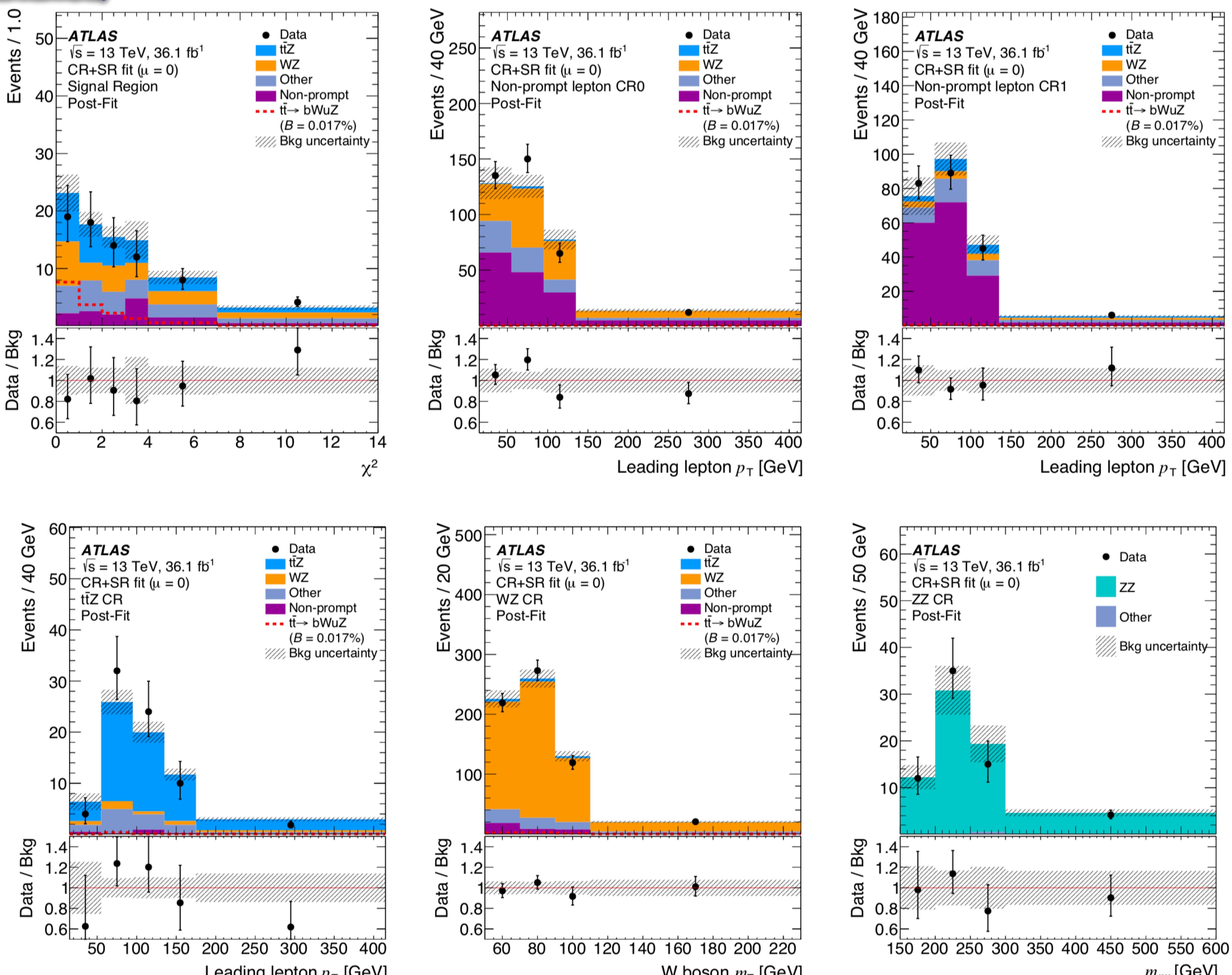
→ leading p_T for non-prompt leptons for $t\bar{t}Z$ (CR)

→ transverse mass for WZ (CR)

→ reco mass for ZZ (CR)

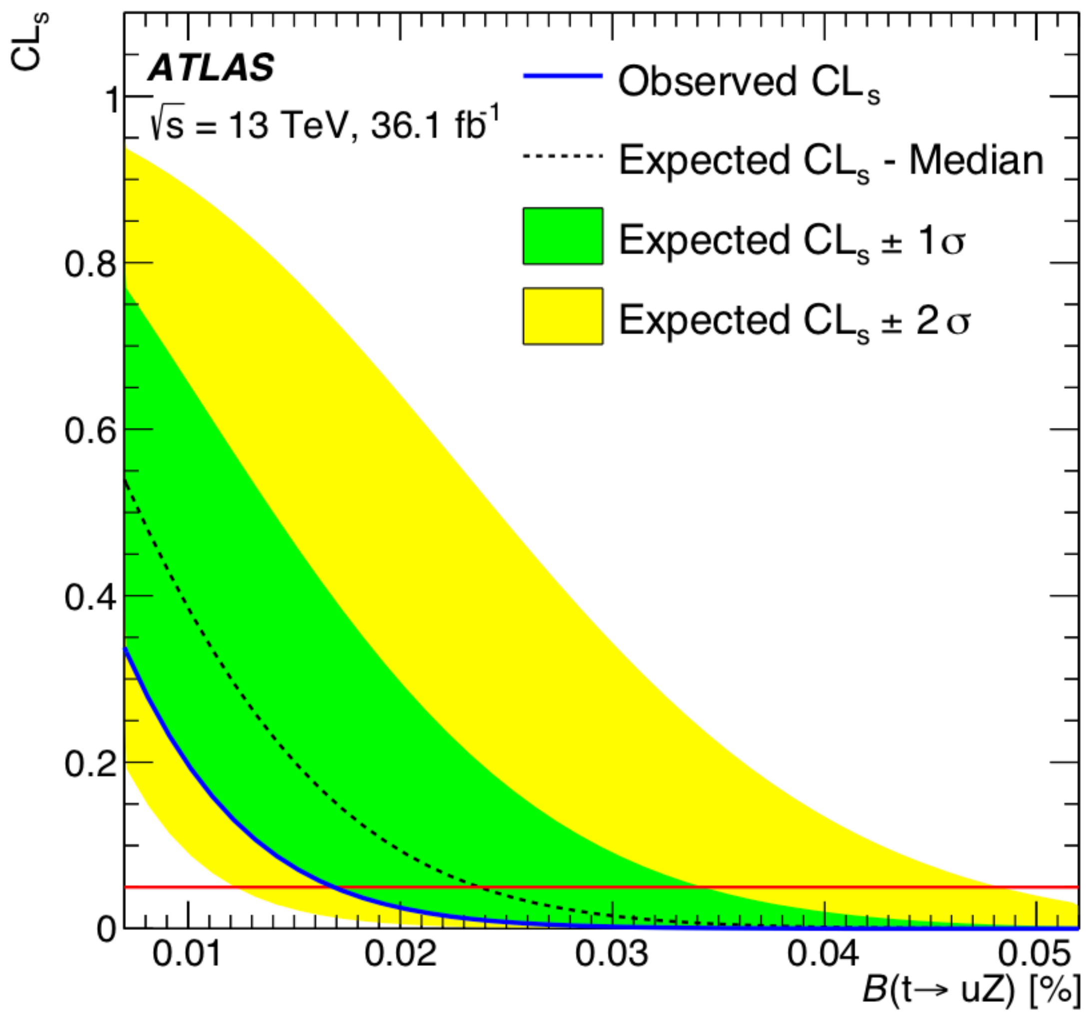
$t \to Zq$

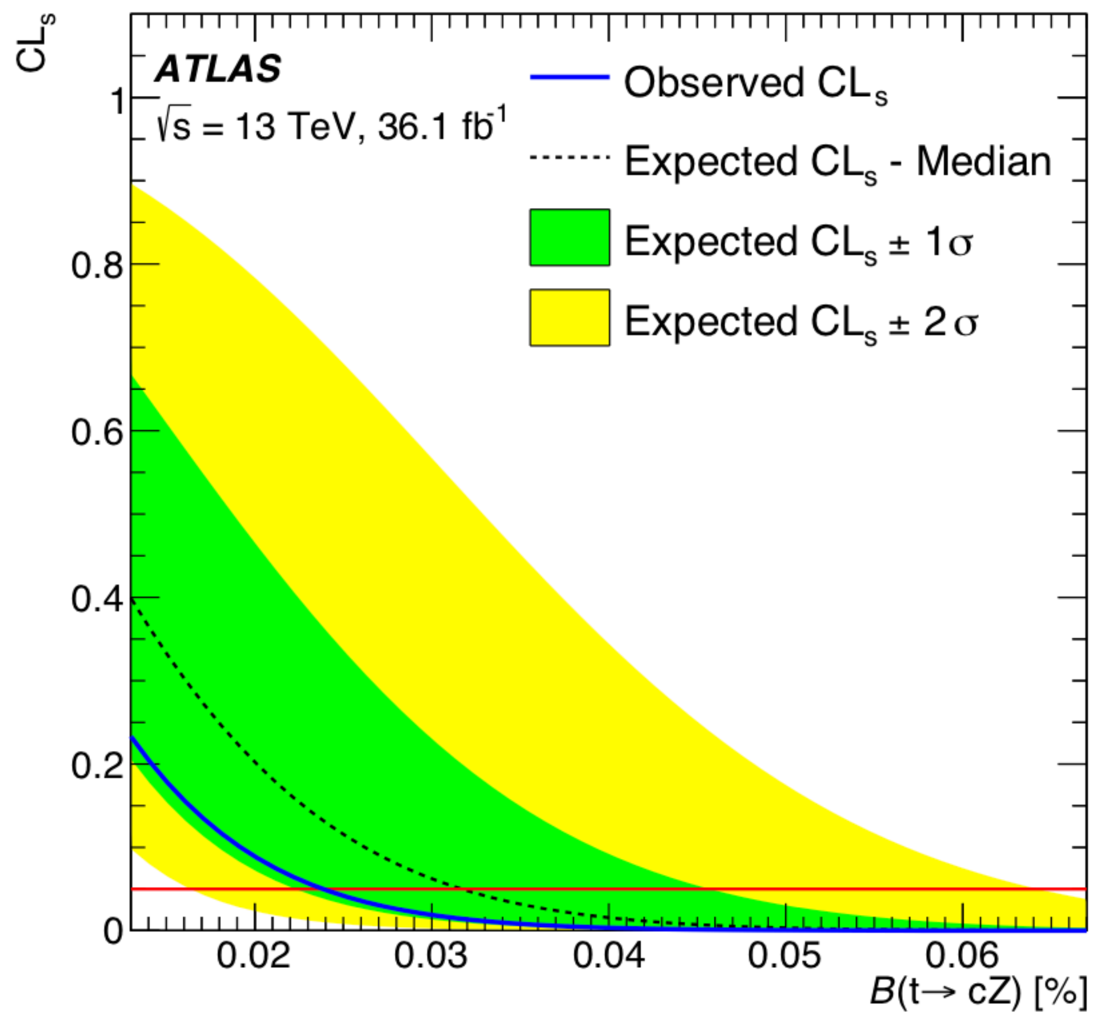
$t\bar{t} \to WbZ(\ell\ell)q$



$t \rightarrow Zq$

$t\bar{t} \rightarrow WbZ(\ell\ell)q$



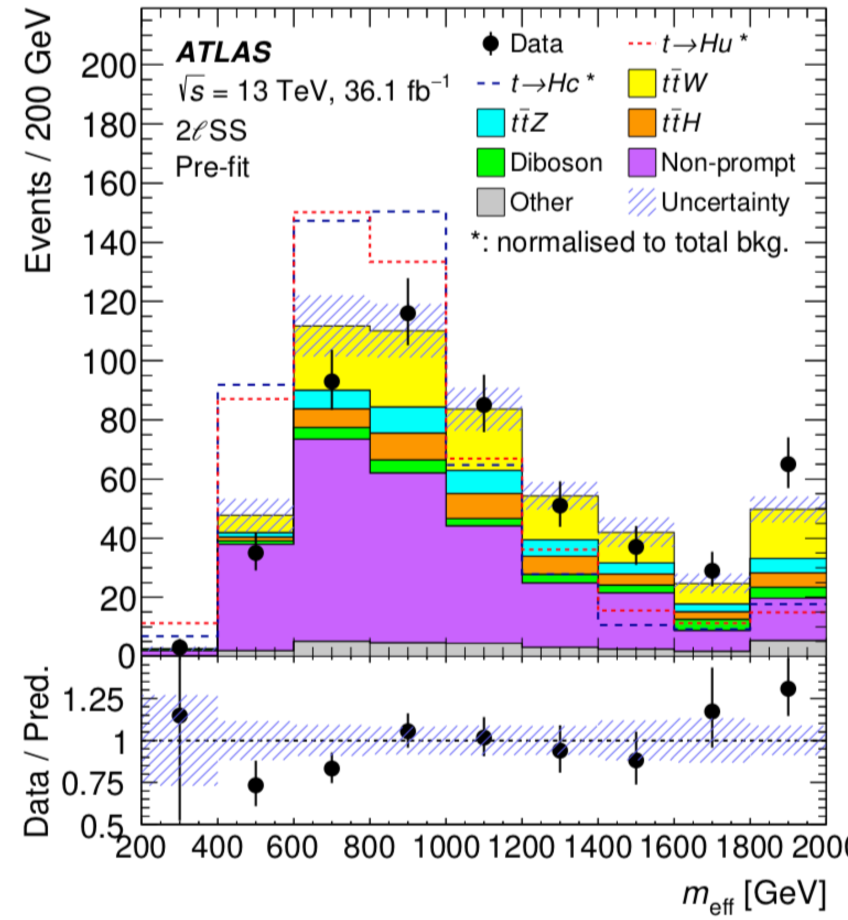


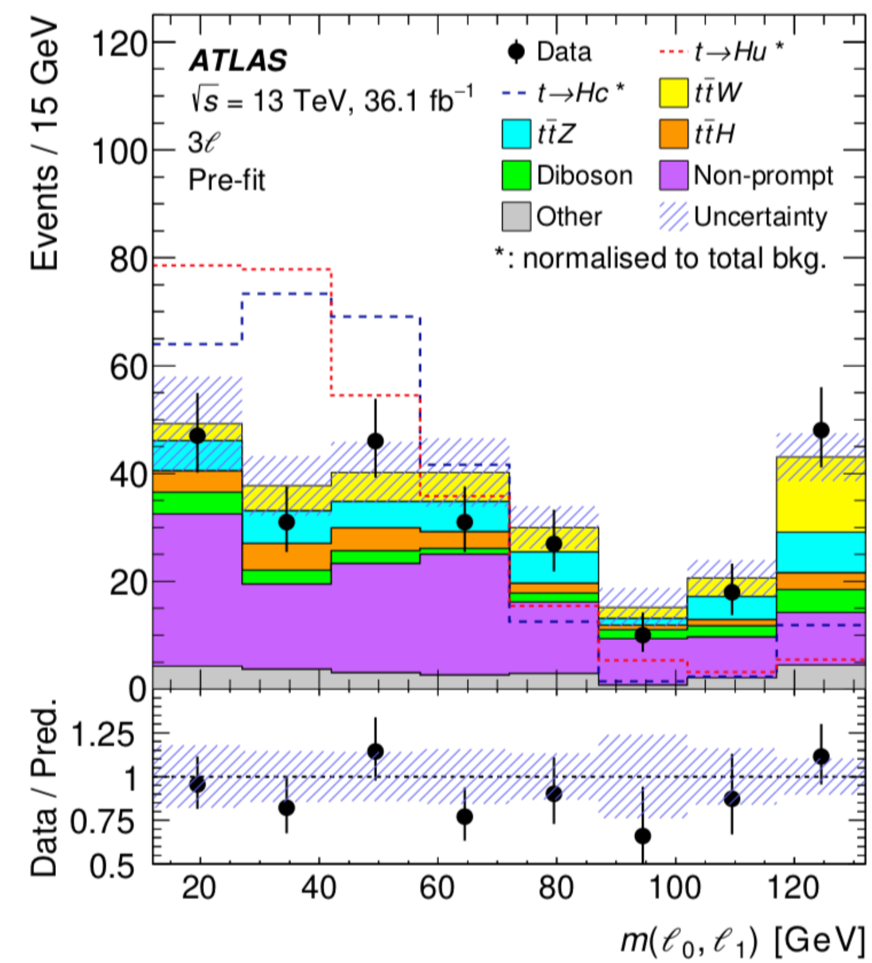
	Expected	Observed
t —> Zu	2.4×10^{-4}	1.7×10^{-4}
t —> Zc	3.2×10^{-4}	2.4×10^{-4}

$t \to H(WW^*/ZZ^*)q$

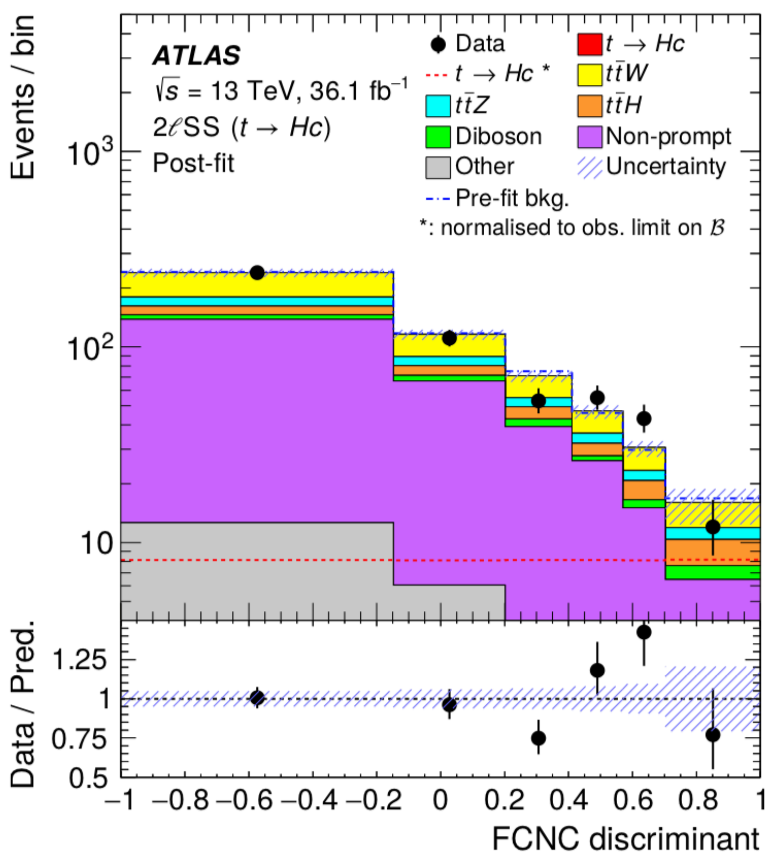
BDT inputs per region category:

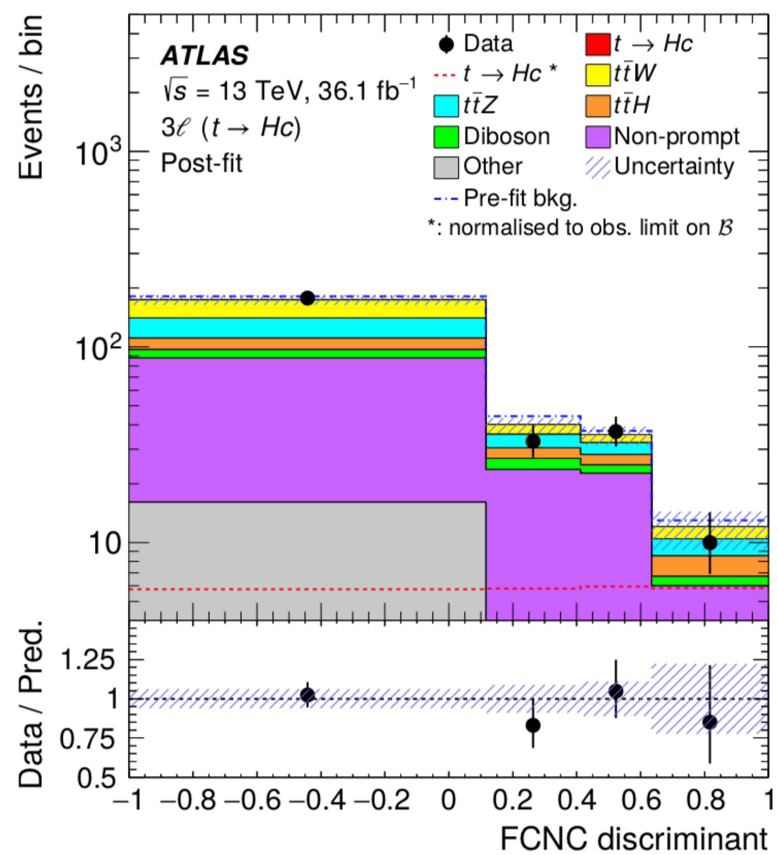
Variable	$2\ell SS$	3ℓ
p_T of higher-p_T lepton	×	
p_T of lower-p_T lepton	×	
p_T of lepton ℓ_0		×
p_T of lepton ℓ_1		×
p_T of lepton ℓ_2		×
Dilepton invariant masses (all combinations)	×	×
Trilepton invariant mass		×
Best Z candidate invariant mass		×
Maximum lepton $\lvert\eta\rvert$	×	
Lepton flavor	×	
Number of jets	×	×
Number of b-tagged jets	×	×
p_T of highest-p_T jet		×
p_T of second highest-p_T jet		×
p_T of highest-p_T b-tagged jet		×
$\Delta R(\ell_0, \ell_1)$		×
$\Delta R(\ell_0, \ell_2)$		×
ΔR(higher-p_T lepton, closest jet)	×	
ΔR(lower-p_T lepton, closest jet)	×	
$\Delta R(\ell_1$, closest jet)		×
Smallest $\Delta R(\ell_0$, b-tagged jet)		×
E_T^{miss}	×	
m_{eff}	×	×

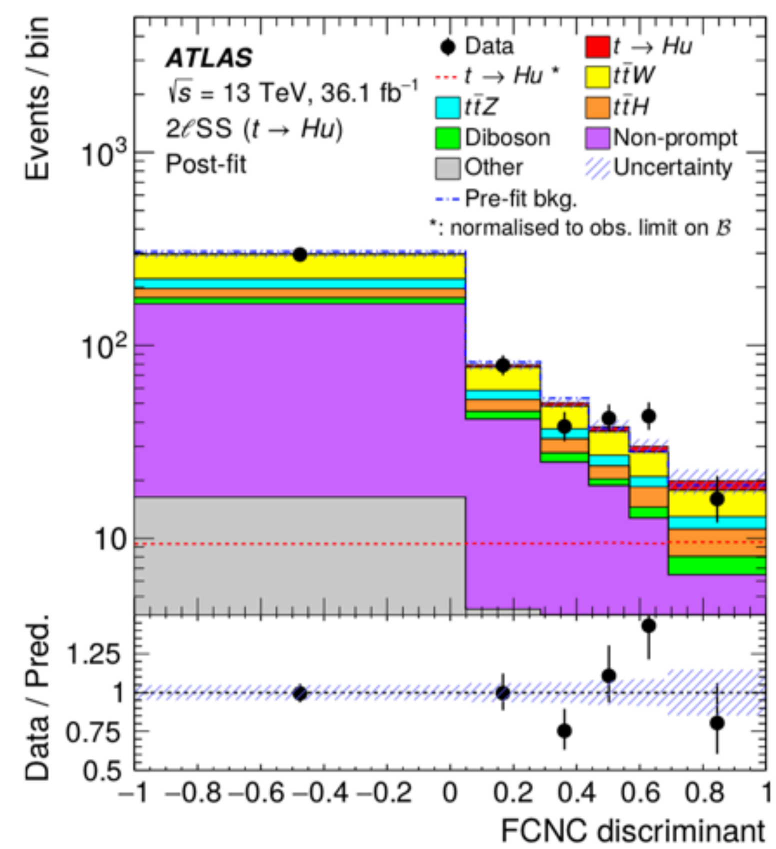


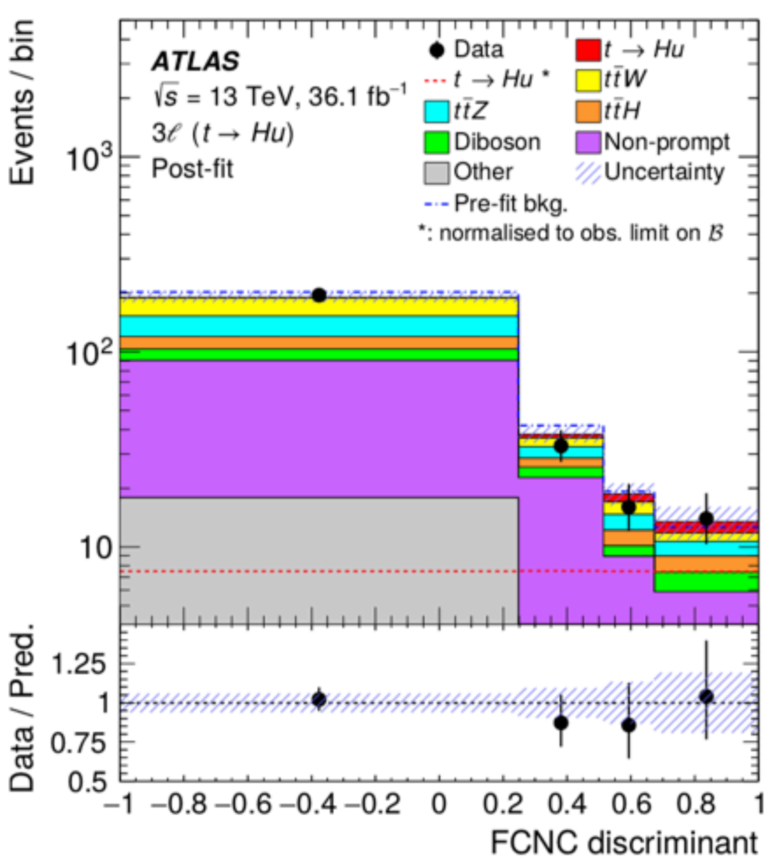


$t \to H(WW^*/ZZ^*)q$



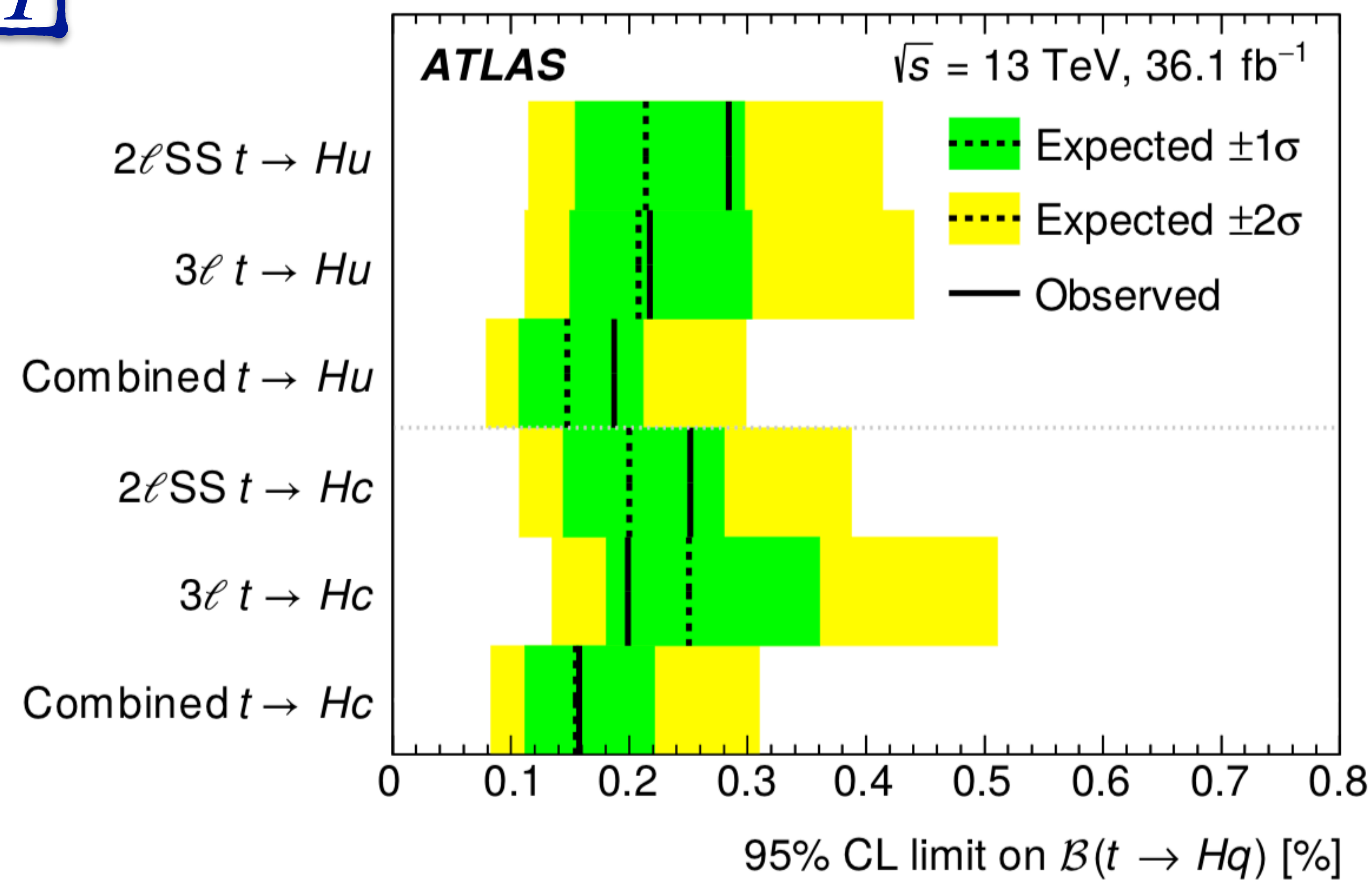






Category		Non-prompt leptons	$t\bar{t}V$	$t\bar{t}H$	Diboson	Other prompt SM	Total SM	FCNC	Data
				$t \to Hu$					
2ℓSS	Pre-fit	266 ± 40	165 ± 19	43 ± 4	25 ± 15	28 ± 6	526 ± 39	61 ± 13	514
	Post-fit	240 ± 37	167 ± 18	43 ± 4	24 ± 14	28 ± 6	502 ± 33	13 ± 21	
3ℓ	Pre-fit	126 ± 31	84 ± 8	23 ± 3	20 ± 11	24 ± 5	276 ± 33	32 ± 6	258
	Post-fit	104 ± 20	84 ± 8	23 ± 3	19 ± 10	24 ± 5	254 ± 18	7 ± 11	
				$t \to Hc$					
2ℓSS	Pre-fit	266 ± 40	165 ± 19	43 ± 4	25 ± 15	28 ± 6	526 ± 39	62 ± 13	514
	Post-fit	264 ± 41	165 ± 18	42 ± 4	20 ± 11	28 ± 6	520 ± 36	−3 ± 25	
3ℓ	Pre-fit	126 ± 31	84 ± 8	23 ± 3	20 ± 11	24 ± 5	276 ± 33	30 ± 6	258
	Post-fit	116 ± 21	84 ± 8	23 ± 3	15 ± 8	23 ± 5	262 ± 19	−1 ± 12	

$t \to H(WW^*/ZZ^*)q$

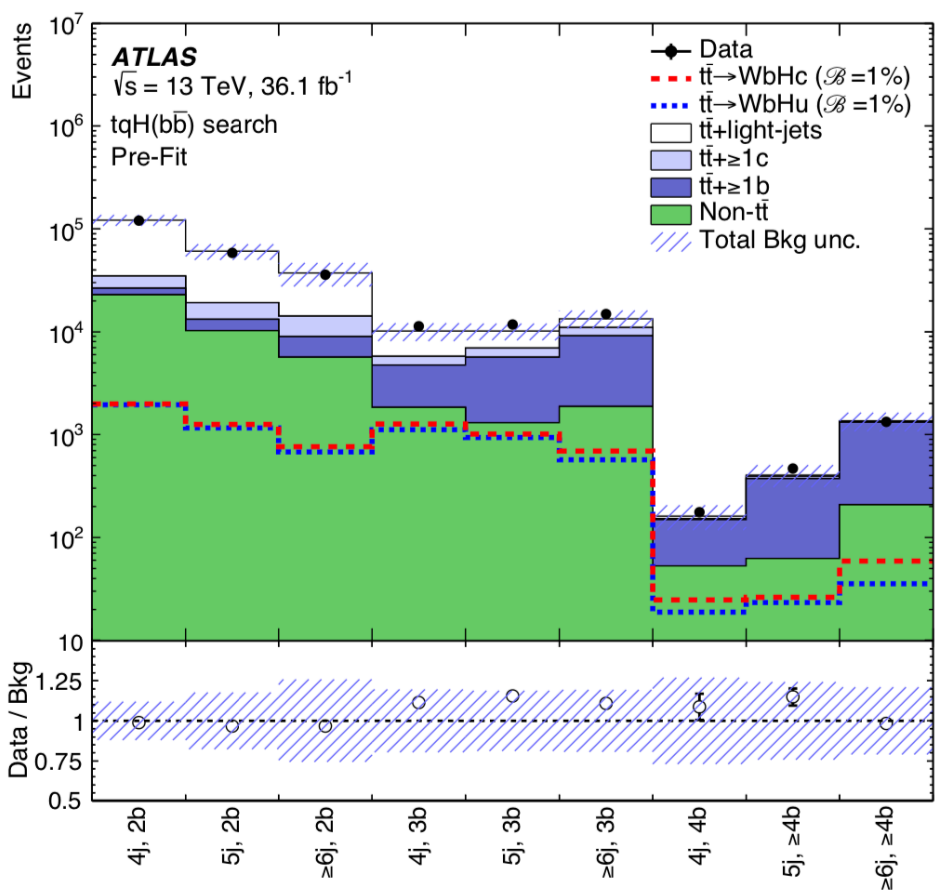


	Expected	Observed
t —> Zu	1.5×10^{-3}	1.6×10^{-3}
t —> Zc	1.5×10^{-3}	1.9×10^{-3}

$t \to H(b\bar{b})q$

Preselection requirements:

Requirement	$tqH(b\bar{b})$ search
Trigger	single-lepton trigger
Leptons	=1 isolated e or μ
	–
Electric charge (q)	–
Jets	$\geq$4 jets
b-tagging	$\geq$2 b-tagged jets



LH discriminant:

$$L(\mathbf{x}) = \frac{P^{\rm sig}(\mathbf{x})}{P^{\rm sig}(\mathbf{x}) + P^{\rm bkg}(\mathbf{x})}$$

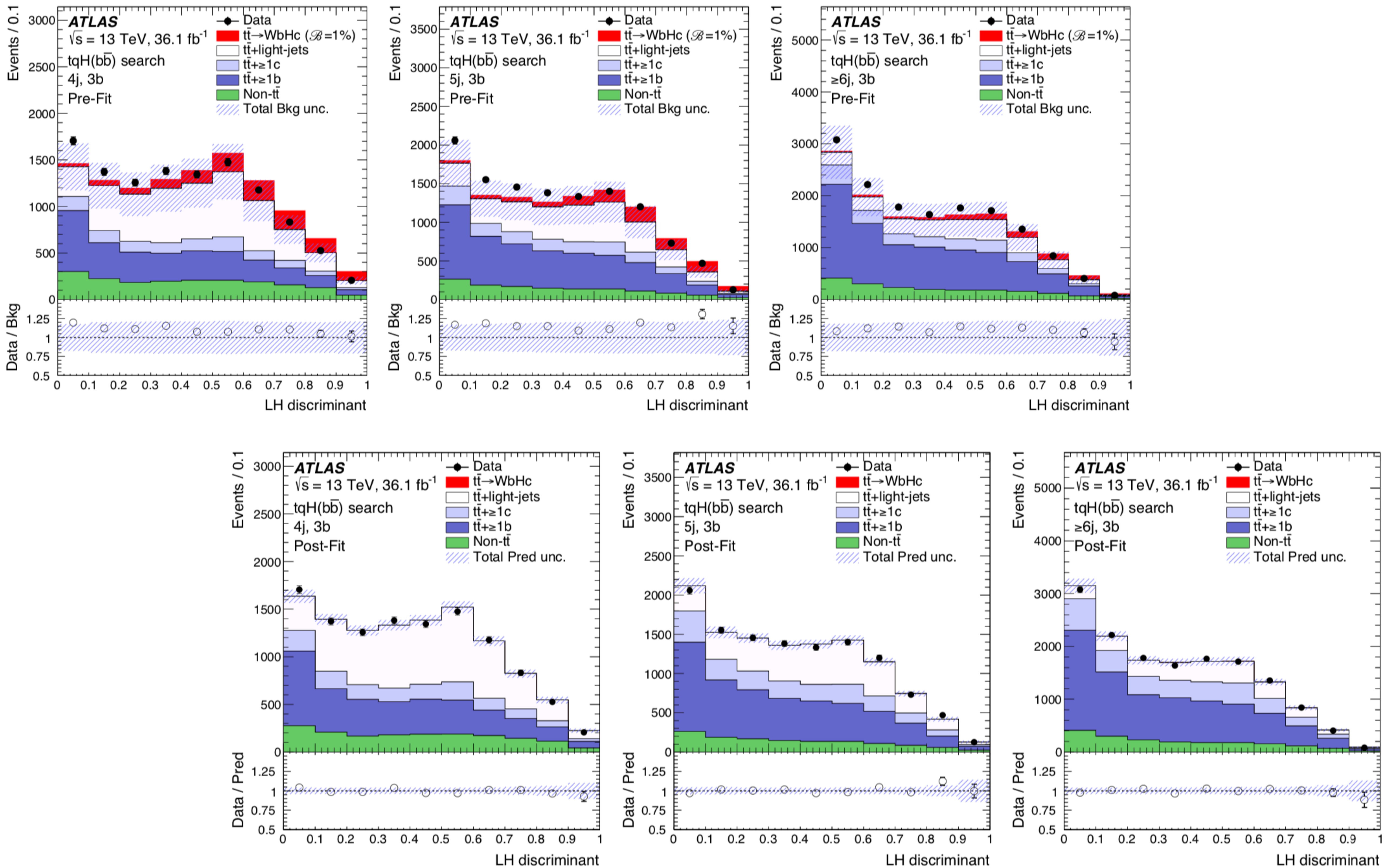
$$P^{\rm sig}(\mathbf{x}) = \frac{\sum_{k=1}^{N_p} P^{\rm sig}_{\rm btag}(\mathbf{x}^k) P^{\rm sig}_{\rm kin}(\mathbf{x}^k)}{\sum_{k=1}^{N_p} P^{\rm sig}_{\rm btag}(\mathbf{x}^k)}$$

$$P^{\rm sig}_{\rm kin}(\mathbf{x}) = P^{\rm sig}(M_{\ell\nu b_\ell}) P^{\rm sig}(X_{b_1 b_2 q_h}) P^{\rm sig}(M_{b_1 b_2})$$

LH discriminant inputs:

- lepton flavour
- kinematic observables (jet prop)
- b-tagging weights
- angular separation
- MET
- m_{eff}

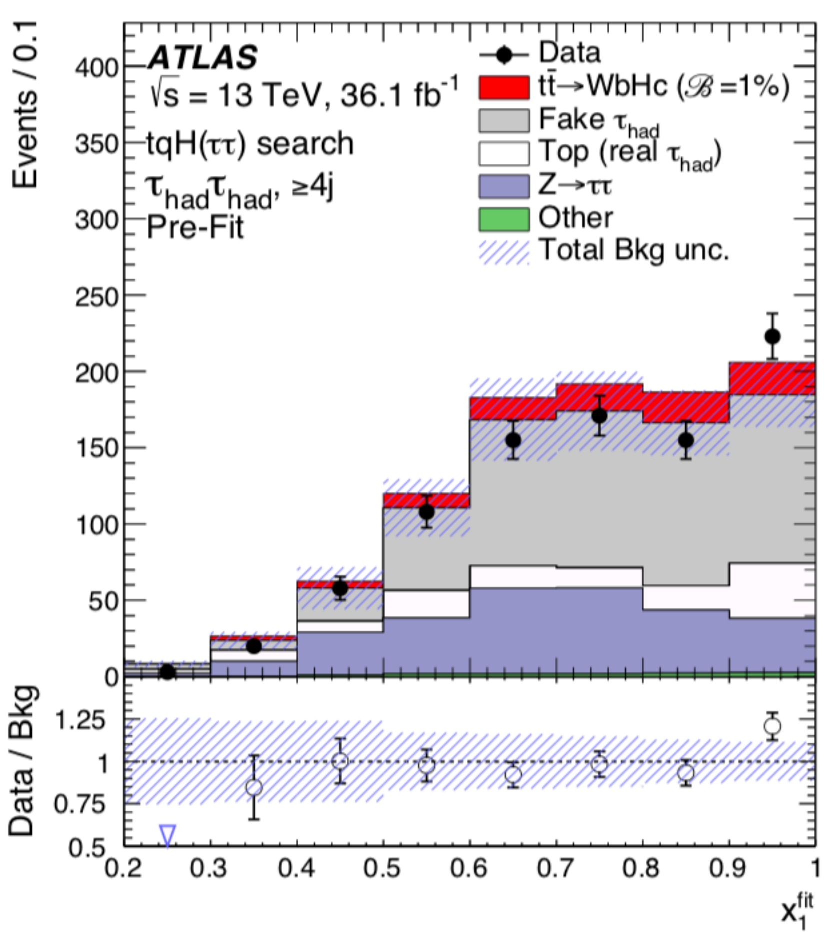
$t \to H(b\bar{b})q$


ATLAS
√s = 13 TeV, 36.1 fb-1
tqH(bb̄) search
4j, 3b
5j, 3b
≥6j, 3b
Pre-Fit
Post-Fit
Data
tt̄→WbHc (ℬ=1%)
tt̄→WbHc
tt̄+light-jets
tt̄+≥1c
tt̄+≥1b
Non-tt̄
Total Bkg unc.
Total Pred unc.
Events / 0.1
Data / Bkg
Data / Pred
LH discriminant

$t \to H(\tau\tau)q$

Preselection requirements:

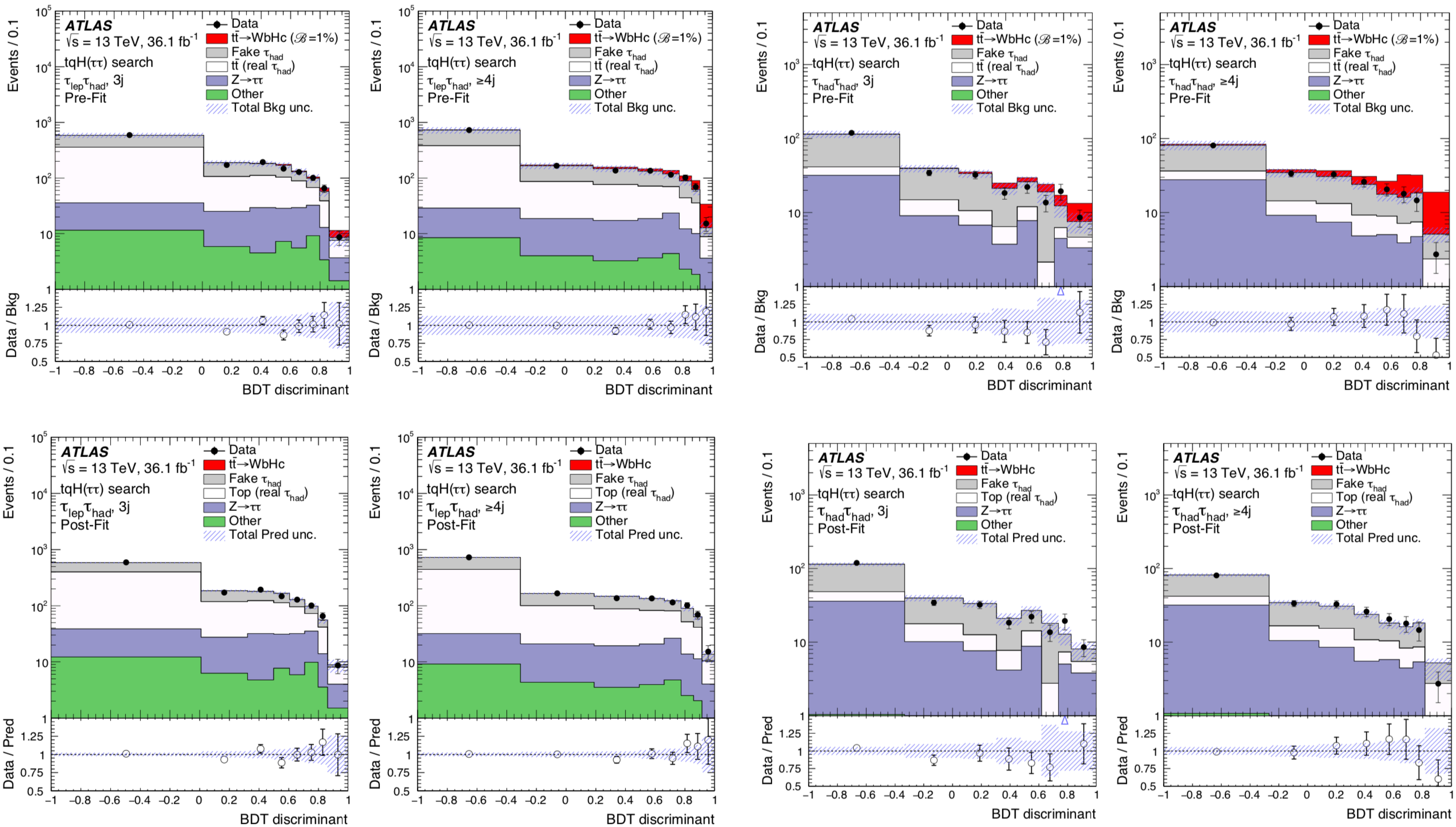
Requirement	$tqH(\tau\tau)$ search $\tau_{lep}\tau_{had}$ channel	$tqH(\tau\tau)$ search $\tau_{had}\tau_{had}$ channel
Trigger	single-lepton trigger	di-τ trigger
Leptons	=1 isolated e or μ	no isolated e or μ
	$\geq 1\ \tau_{had}$	$\geq 2\ \tau_{had}$
Electric charge (q)	$q_\ell \times q_{\tau_{had,1}} < 0$	$q_{\tau_{had,1}} \times q_{\tau_{had,2}} < 0$
Jets	≥ 3 jets	≥ 3 jets
b-tagging	=1 b-tagged jets	=1 b-tagged jets



BDT input variables:

Variable	$\tau_{lep}\tau_{had}$ 3j	$\tau_{lep}\tau_{had}$ $\geq$4j	$\tau_{had}\tau_{had}$ 3j	$\tau_{had}\tau_{had}$ $\geq$4j
$m_{\tau\tau}^{fit}$	×	×	×	×
m_{Hq}	×	×	×	×
$m_{T,lep}$	×	×		
$p_{T,1}$	×	×	×	×
$p_{T,2}$	×	×	×	×
E_T^{miss} ϕ centrality	×	×	×	×
$E_{T,\parallel}^{miss}$	×	×	×	×
$E_{T,\perp}^{miss}$	×	×		
m_{bj_1}	×	×	×	×
m_{lepj}	×	×		
$m_{\tau j}$	×	×		
x_1^{fit}	×	×	×	×
x_2^{fit}	×	×	×	×
$m_{bj_1j_2}$		×		×

$t \to H(\tau\tau)q$



$t \to H(b\bar{b})q$

$t \to H(\tau\tau)q$

H —> bb	Expected	Observed
t —> Hu	4.9×10^{-3}	5.2×10^{-3}
t —> Hc	4.0×10^{-3}	4.2×10^{-3}

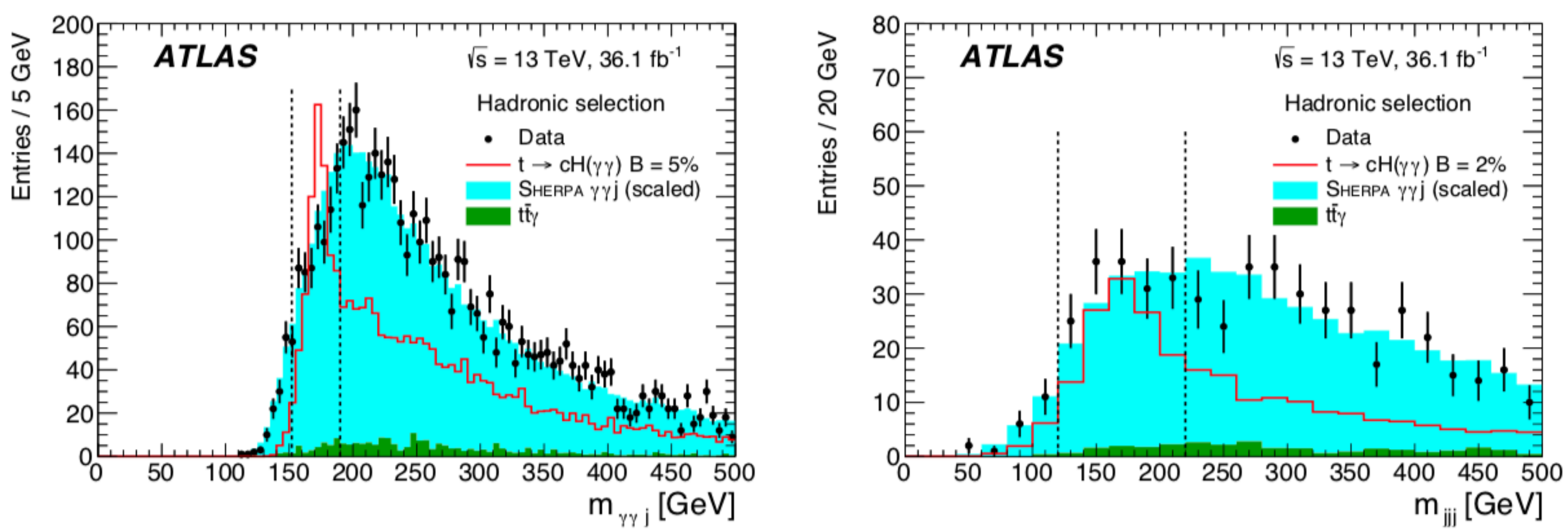
H —> tau tau	Expected	Observed
t —> Hu	2.0×10^{-3}	1.7×10^{-3}
t —> Hc	2.1×10^{-3}	1.9×10^{-3}

$t \to H(\gamma\gamma)q$

Hadronic selection

The next step is designed to select events for which the six-body final state (two photons and four jets) is compatible with a $t\bar{t}$ final state. It starts by forming three-body objects: the two photons plus one jet on one side (Top1), and the three other jets on the other side (Top2). By grouping each of the four jets with the two photons, four (Top1,Top2) pairs are constructed, with corresponding invariant masses (M_1,M_2). For an event to be selected, there must be at least one combination (Top1,Top2) with masses (M_1,M_2) compatible with the top quark mass, as decribed below.[5]

Based on the position and width of the two signal peaks, the window chosen for the M_1 selection ranges from 152 GeV to 190 GeV, while for M_2 the broader range from 120 GeV to 220 GeV is chosen.



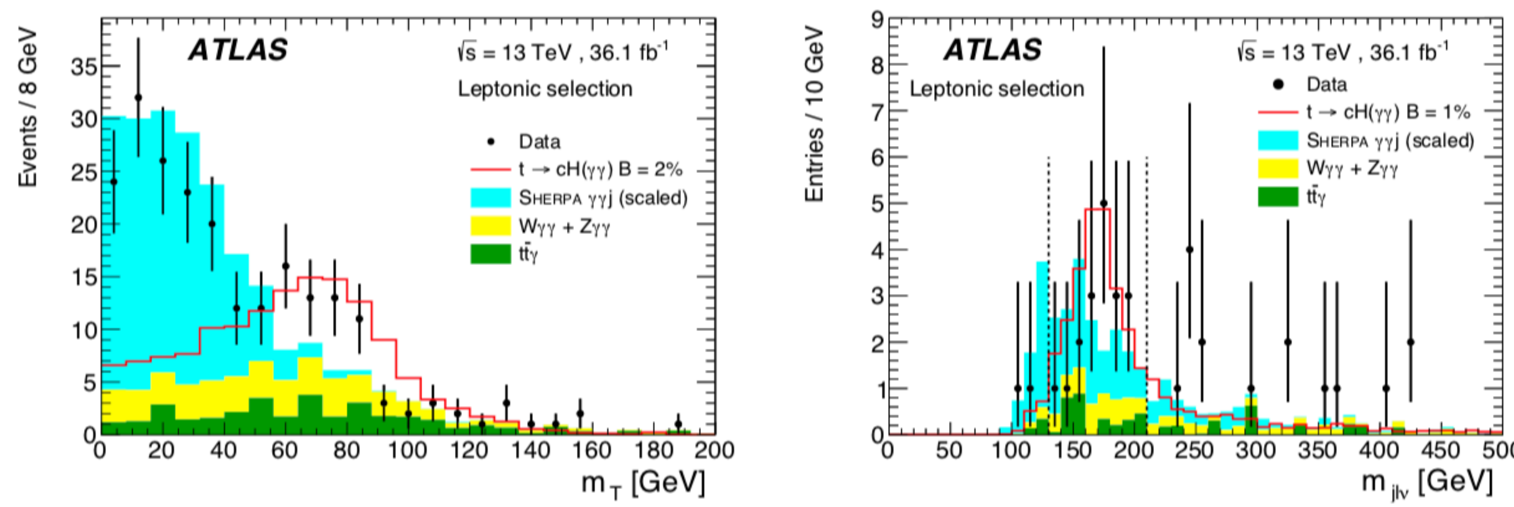
In order to increase the acceptance, albeit with a reduced signal-to-noise ratio, events failing the M_2 selection step are also retained for the final analysis by exploiting two (orthogonal) categories:

- category 1: events that pass the full selection;
- category 2: events that fail the M_2 requirement but satisfy all other selection criteria.

$t \rightarrow H(\gamma\gamma)q$

Leptonic selection

The next step is to verify, as was done for the hadronic selection, that the final-state particles are kinematically compatible with the decay of two top quarks. The invariant mass M_1 of the two photons and one of the two jets (Top1) is calculated, as well as the mass M_2 of the remaining jet, the lepton, and the neutrino (Top2). For the latter, the neutrino longitudinal momentum is estimated by using a W boson mass constraint, as was done in Ref. [33]. The same calculation is repeated, exchanging the role of the two jets. If the invariant masses (M_1, M_2) of one of the two (Top1, Top2) combinations fall in predefined windows around the top quark mass, the event is selected, provided one of the two jets is b-tagged. This defines category-1 events. Events fulfilling all requirements, except the one on M_2 are kept as category-2 events. As was done for the hadronic mode, the acceptance windows were optimised, resulting in the same interval for M_1 (152 GeV to 190 GeV), and in a slightly narrower interval for M_2, from 130 GeV to 210 GeV.

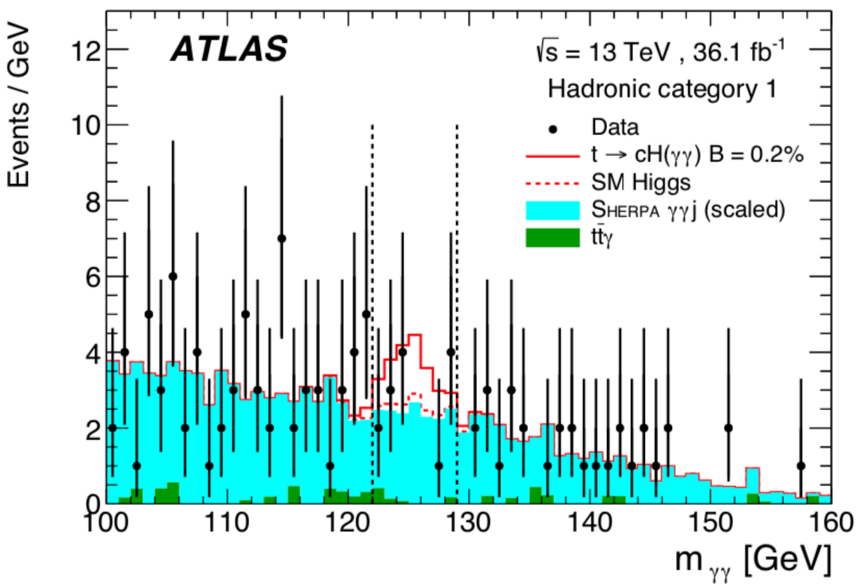


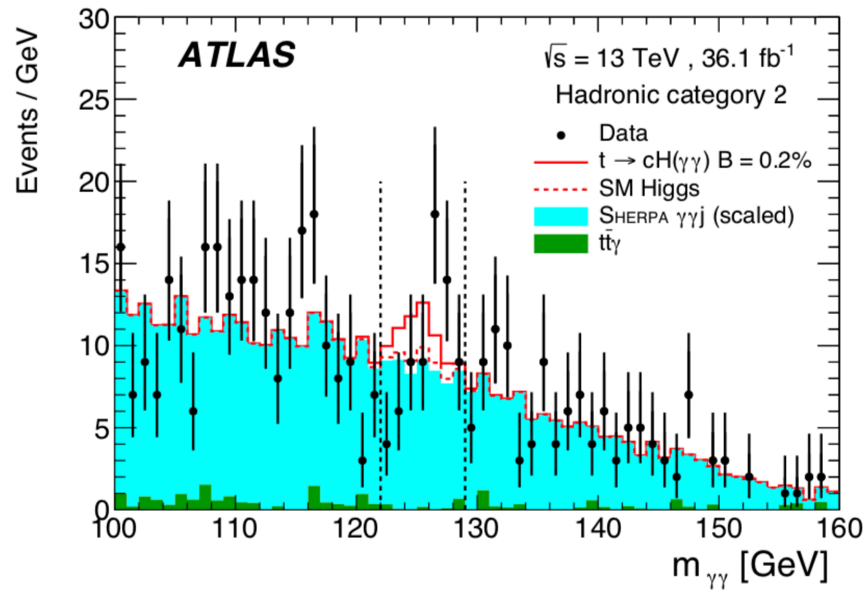
(a) (b)

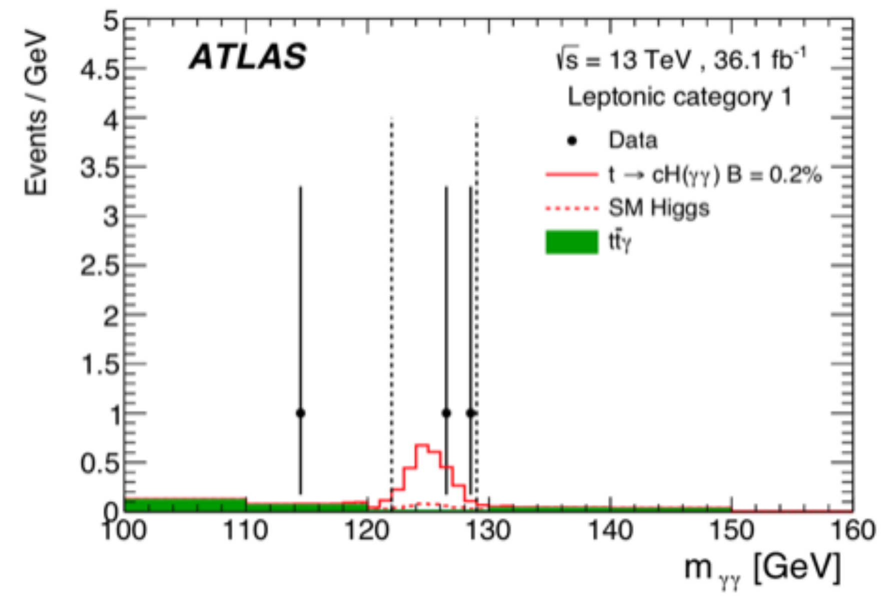
Figure 3: Distribution (a) of the transverse mass calculated from the lepton kinematics and the missing transverse momentum and (b) of the invariant mass of the lepton, the neutrino, and one jet for each $\gamma\gamma j$ combination where the $m_{\gamma\gamma j}$ mass falls in the M_1 acceptance window. No b-tagging is required. The $t\bar{t}\gamma$, $W\gamma\gamma$ and $Z\gamma\gamma$ distributions are superimposed, normalised to the data's integrated luminosity using theoretical cross sections. The SHERPA $S_{\gamma\gamma j}$ sample is normalised to the difference between data and the sum of $t\bar{t}\gamma$, $W\gamma\gamma$ and $Z\gamma\gamma$. The distribution of the FCNC signal is normalised assuming a branching ratio of (a) 2% and (b) 1%. The vertical dotted lines in (b) indicate the M_2 selection window (see text).

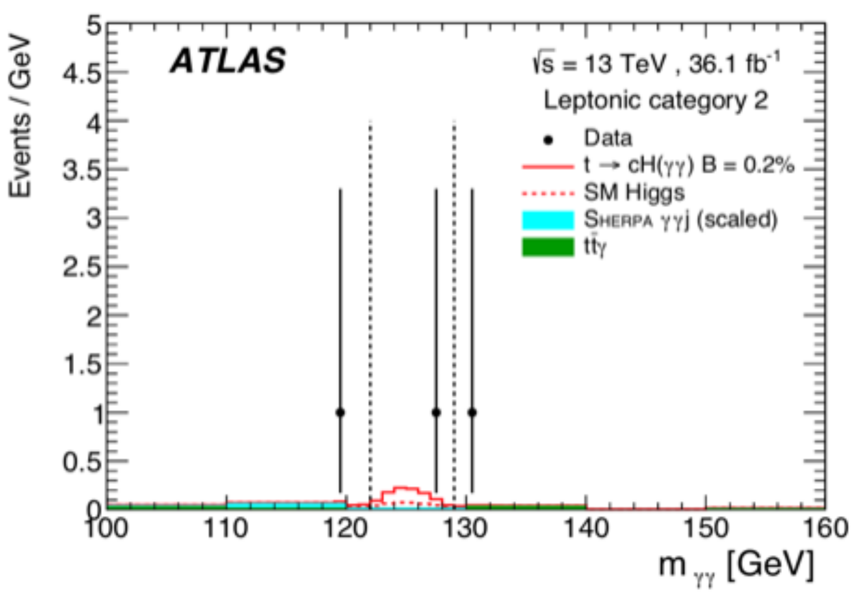
$t \to H(\gamma\gamma)q$

$m_{\gamma\gamma}$ distributions after the hadronic/leptonic selection



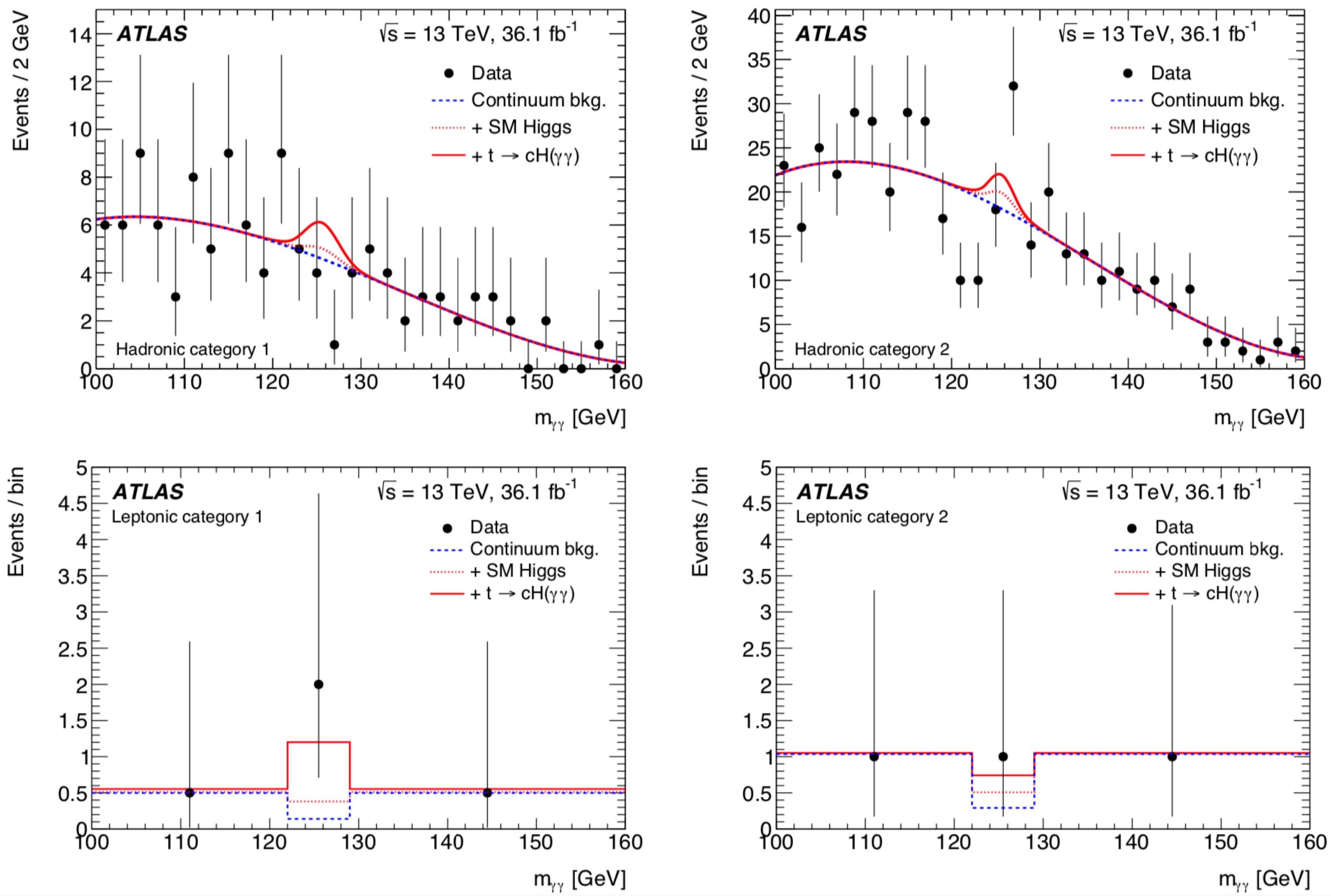






Selection	Hadronic		Leptonic	
Category	1	2	1	2
	Signal $t \to cH$			
Acceptance with stat. unc. [%]	2.89 ± 0.10	4.15 ± 0.12	0.96 ± 0.03	0.27 ± 0.02
Expected events for $\mathcal{B} = 0.2\%$	$7.85^{+0.64}_{-0.67}$	$11.30^{+0.91}_{-0.96}$	$2.60^{+0.21}_{-0.23}$	$0.71^{+0.07}_{-0.07}$
	SM Higgs boson resonant background			
Expected events	$1.17^{+0.09}_{-0.11}$	$3.27^{+0.25}_{-0.27}$	$0.26^{+0.02}_{-0.03}$	$0.23^{+0.02}_{-0.02}$
$t\bar{t}H$ fraction	90%	68%	92%	77%

$t \to H(\gamma\gamma)q$



$\mathscr{B}$ limits were also translated to off diagonal Yukawa couplings following:

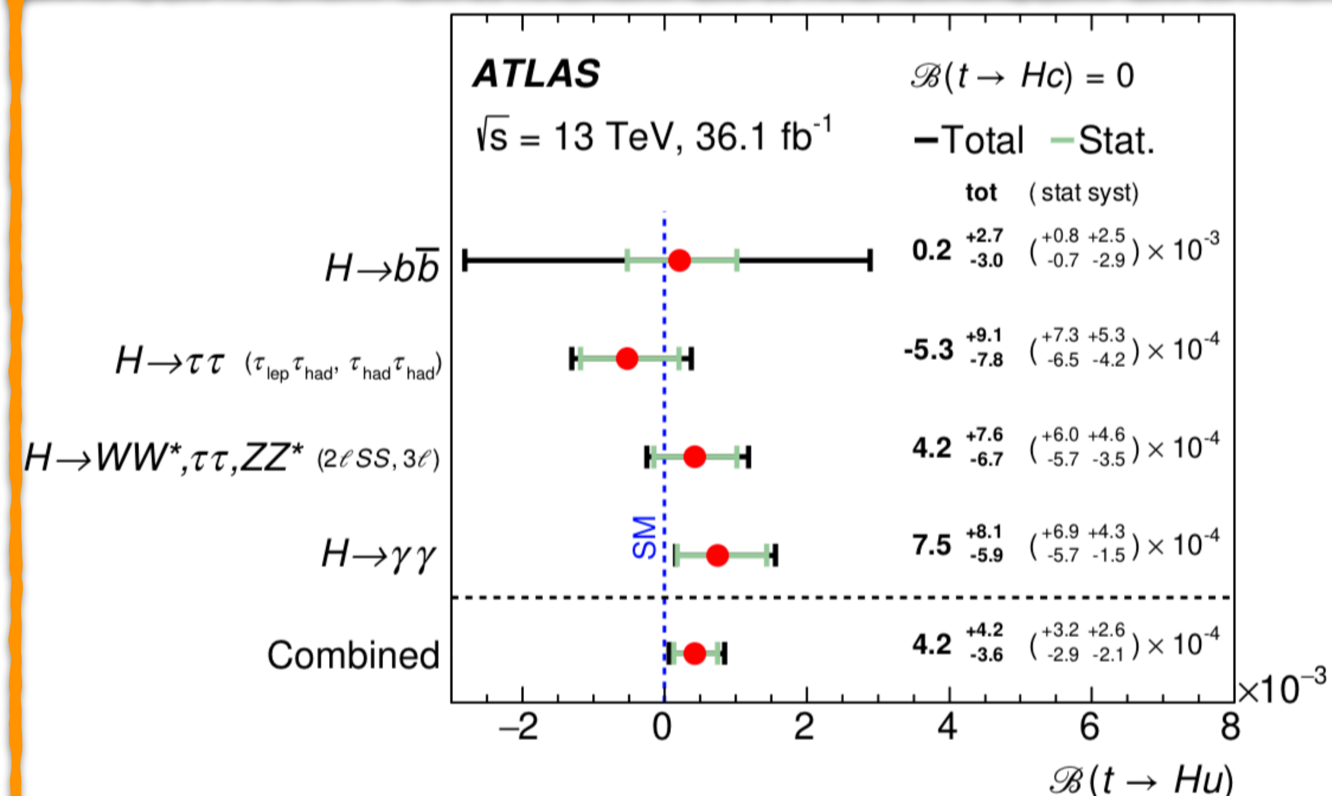
$\lambda_{tqH} = (1.92 \pm 0.02) \times \sqrt{\mathscr{B}}$

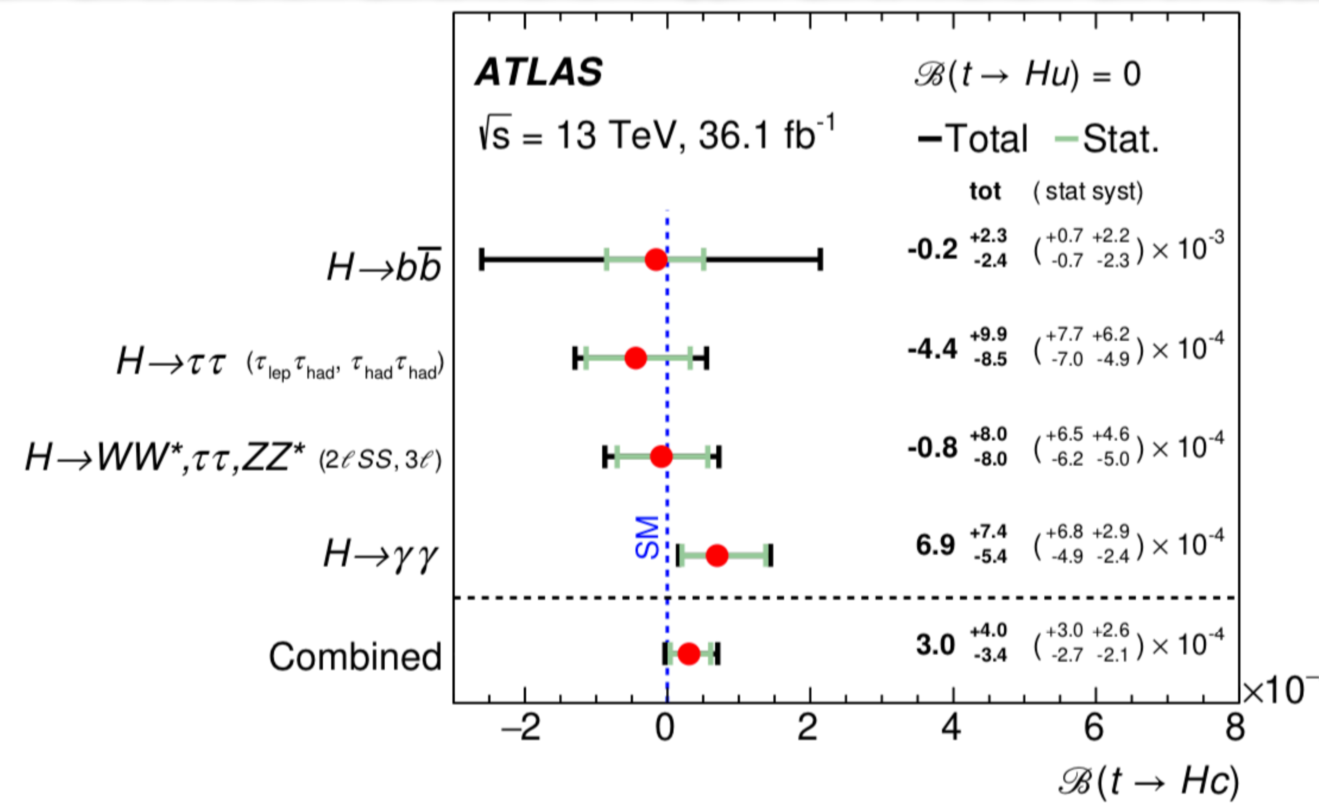
resulting in:

$$\sqrt{\lambda_{tcH}^2 + 0.92\lambda_{tuH}^2} < 0.090$$

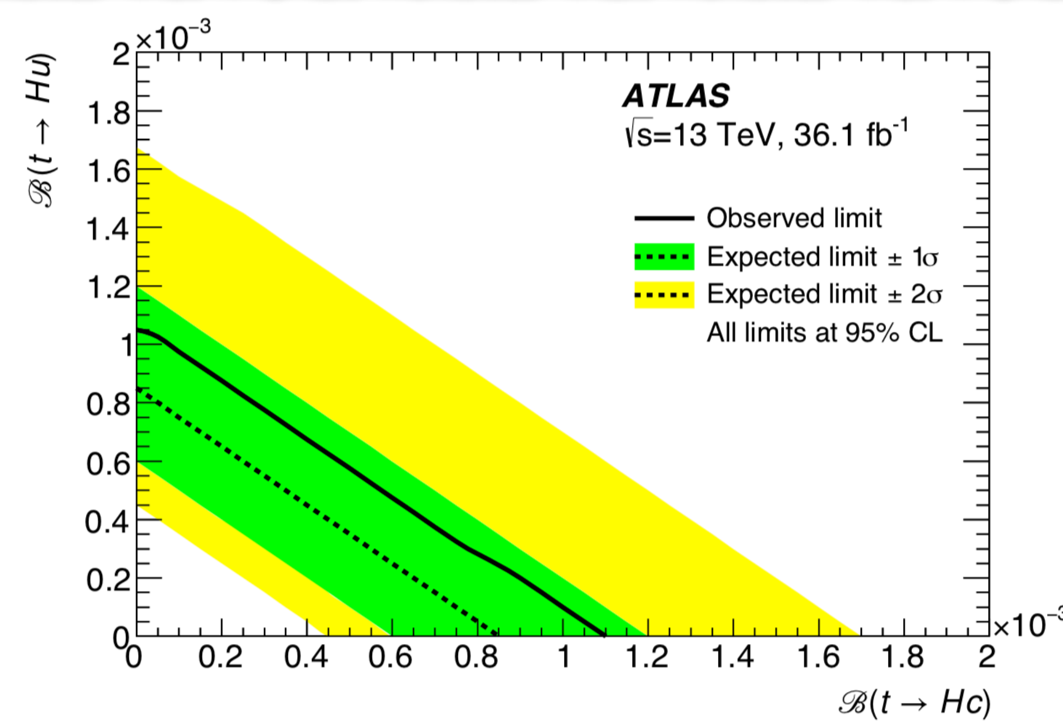
H —> gam gam	Expected	Observed
t —> Hu	2.4×10^{-3}	1.7×10^{-3}
t —> Hc	1.6×10^{-3}	2.2×10^{-3}

$t \rightarrow Hq$ Combination





Summary of the best-fit $\mathscr{B}(t \rightarrow Hq)$for the individual searches as well as their combination, assuming $\mathscr{B}(t \rightarrow Hq') = 0$, where $q, q' = u, c$.



$t \to Hq$ Combination

- upper limits on $\mathscr{B}(t \to Hq)$ were translated into upper limits on the non-flavour-diagonal Yukawa couplings λ_{tqH} appearing in the Lagrangian

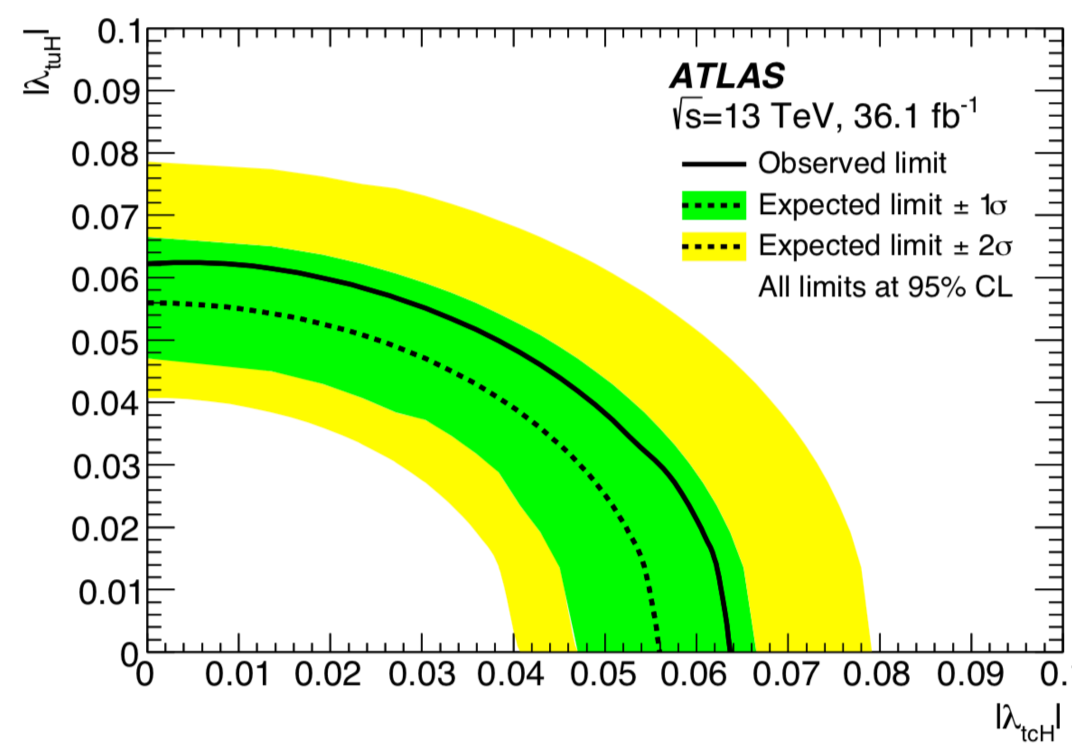
- $\mathscr{L}_{\text{FCNC}} = -\lambda_{t_L q_R}\bar{t}_L q_R H - \lambda_{q_L t_R}\bar{q}_L t_R H + h.c.$

- $\mathscr{B}(t \to Hq)$ is estimated as the ratio of its partial width to the SM $t \to Wb$ partial width, which is assumed to be dominant

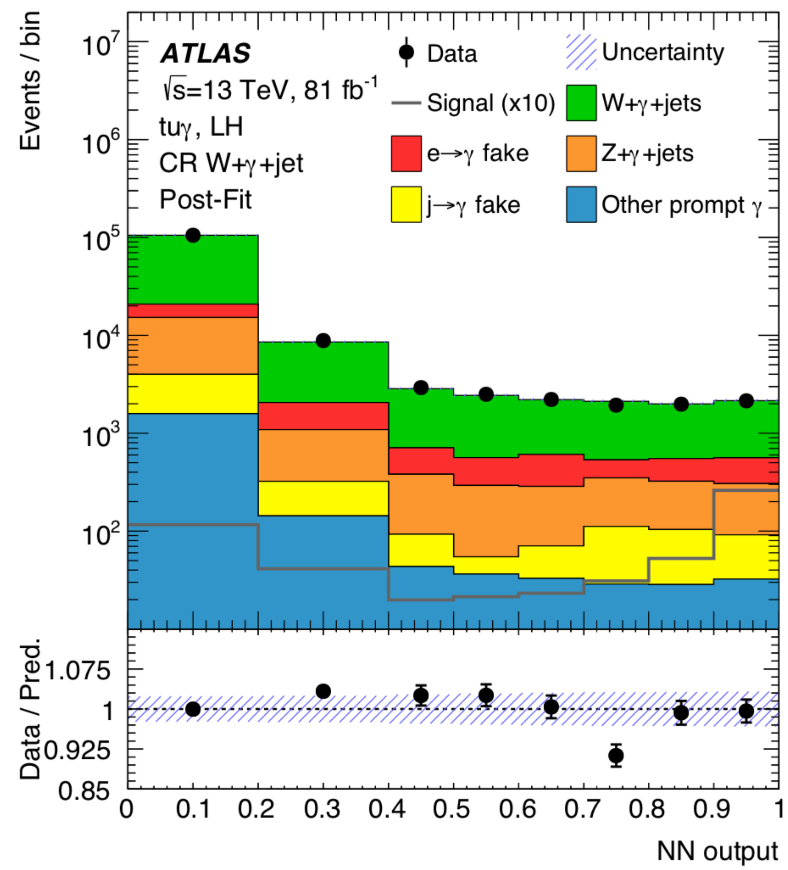
- the coupling $|\lambda_{tqH}|$ can be extracted as $|\lambda_{tqH}| = (1.92 \pm 0.02)\sqrt{\mathscr{B}(t \to Hq)}$

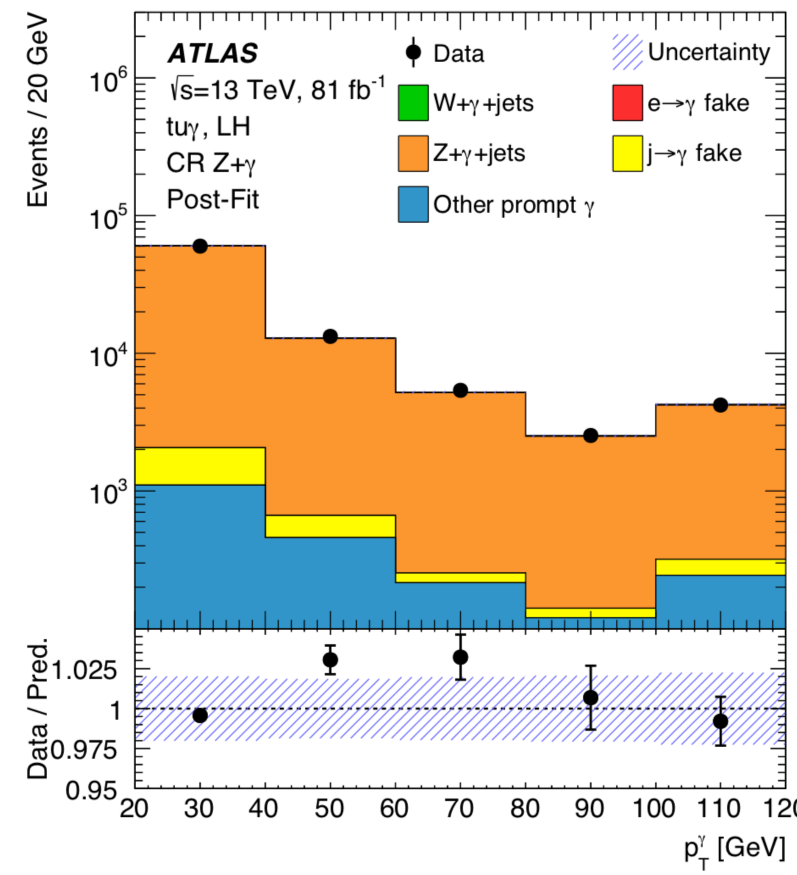
- λ_{tqH} coupling corresponds to the sum in quadrature of the couplings relative to the two possible chirality combinations of the quark fields $\lambda_{tqH} = \sqrt{|\lambda_{t_L q_R}|^2 + |\lambda_{q_L t_R}|^2}$

	Expected	Observed
$\lvert\lambda_{tuH}\rvert$	0.055	0.066
$\lvert\lambda_{tcH}\rvert$	0.055	0.064



$t \to \gamma q$





NN inputs:

- $p_T^{\gamma}, p_T^{lepton}, p_T^{jet}$
- lepton charge
- $\not{E}_T$
- $m_{lep-\gamma}, m_{lep-jet}$
- $\Delta R_{lep-\gamma}, \Delta R_{lep-jet}, \Delta R_{jet-\gamma}$

Observable	Vertex	Coupling	Obs.	Exp.
$\lvert C_{uW}^{(13)*} + C_{uB}^{(13)*} \rvert$	$tu\gamma$	LH	0.19	$0.22^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(31)} + C_{uB}^{(31)} \rvert$	$tu\gamma$	RH	0.27	$0.27^{+0.05}_{-0.04}$
$\lvert C_{uW}^{(23)*} + C_{uB}^{(23)*} \rvert$	$tc\gamma$	LH	0.52	$0.57^{+0.11}_{-0.09}$
$\lvert C_{uW}^{(32)} + C_{uB}^{(32)} \rvert$	$tc\gamma$	RH	0.48	$0.59^{+0.12}_{-0.09}$
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	LH	36	52^{+21}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	RH	78	75^{+31}_{-21}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	LH	40	49^{+20}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	RH	33	52^{+22}_{-14}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	RH	6.1	$5.9^{+2.4}_{-1.6}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	LH	22	27^{+11}_{-7}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	RH	18	28^{+12}_{-8}

} effective coupling strengths (*)
the energy scale is assumed to be $\Lambda = 1\text{TeV}$

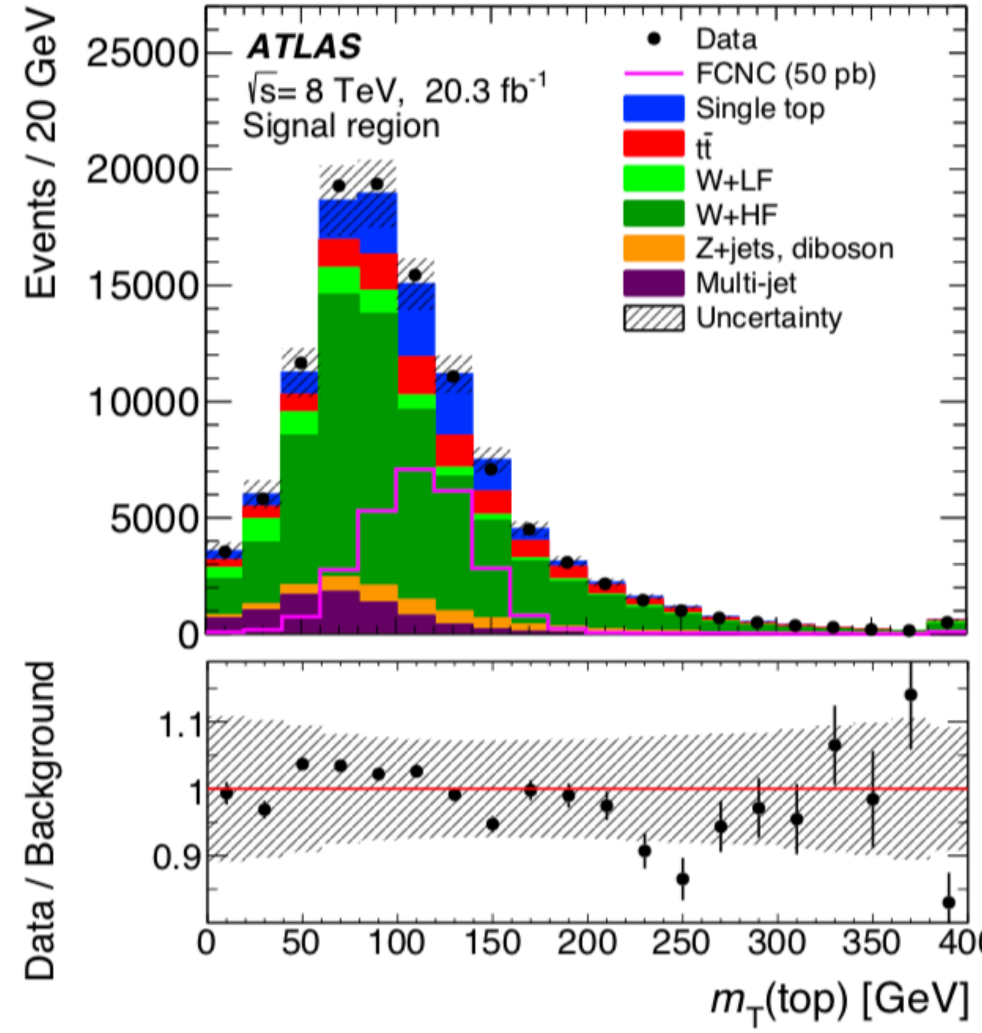
(*) more details in arXiv:0811.3842

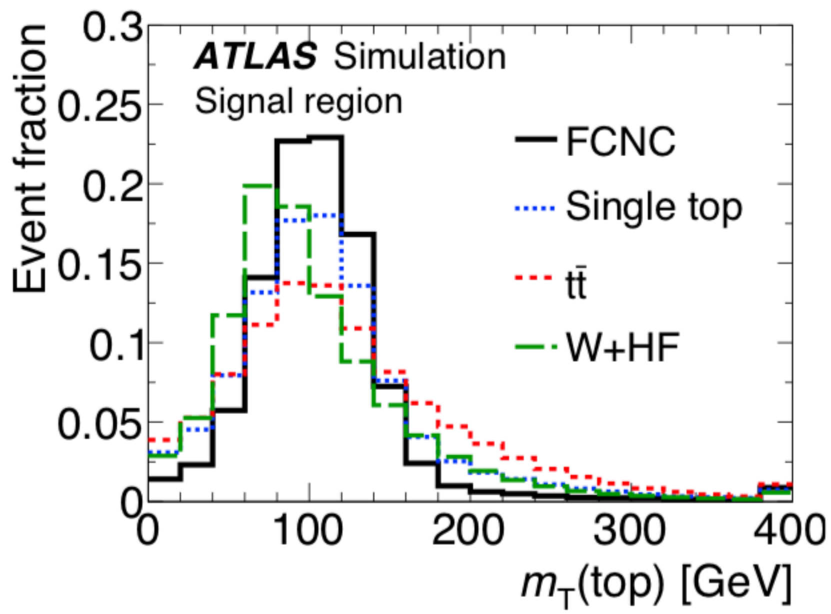
$t \to gq$

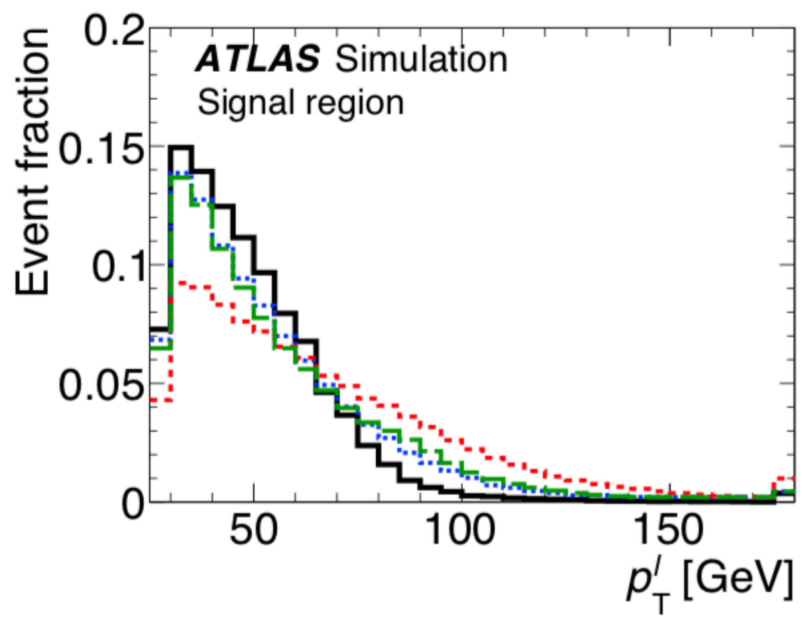
$gq \to t \to W(\to \ell\nu)b$

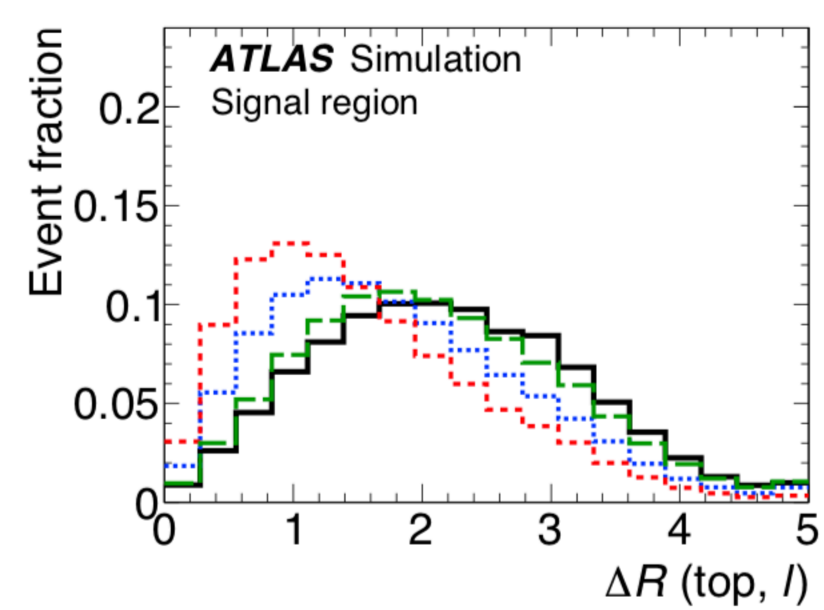
Neural Network input variables:

Variable	Definition
$m_{\mathrm{T}}(\mathrm{top})$	Transverse mass of the reconstructed top quark
p_{T}^{ℓ}	Transverse momentum of the charged lepton
$\Delta R(\mathrm{top}, \ell)$	Distance in the η–ϕ plane between the reconstructed top quark and the charged lepton
$p_{\mathrm{T}}^{b\text{-jet}}$	Transverse momentum of the b-tagged jet
$\Delta\phi(\mathrm{top}, b\text{-jet})$	Difference in azimuth between the reconstructed top quark and the b-tagged jet
$\cos\theta(\ell, b\text{-jet})$	Opening angle of the three-vectors between the charged lepton and the b-tagged jet
q^{ℓ}	Charge of the lepton
$m_{\mathrm{T}}(W)$	W-boson transverse mass
η^{ℓ}	Pseudorapidity of the charged lepton
$\Delta\phi(\mathrm{top}, W)$	Difference in azimuth between the reconstructed top quark and the W boson
$\Delta R(\mathrm{top}, b\text{-jet})$	Distance in the η–ϕ plane between the reconstructed top quark and the b-tagged jet
η^{top}	Pseudorapidity of the reconstructed top quark
p_{T}^{W}	Transverse momentum of the W boson



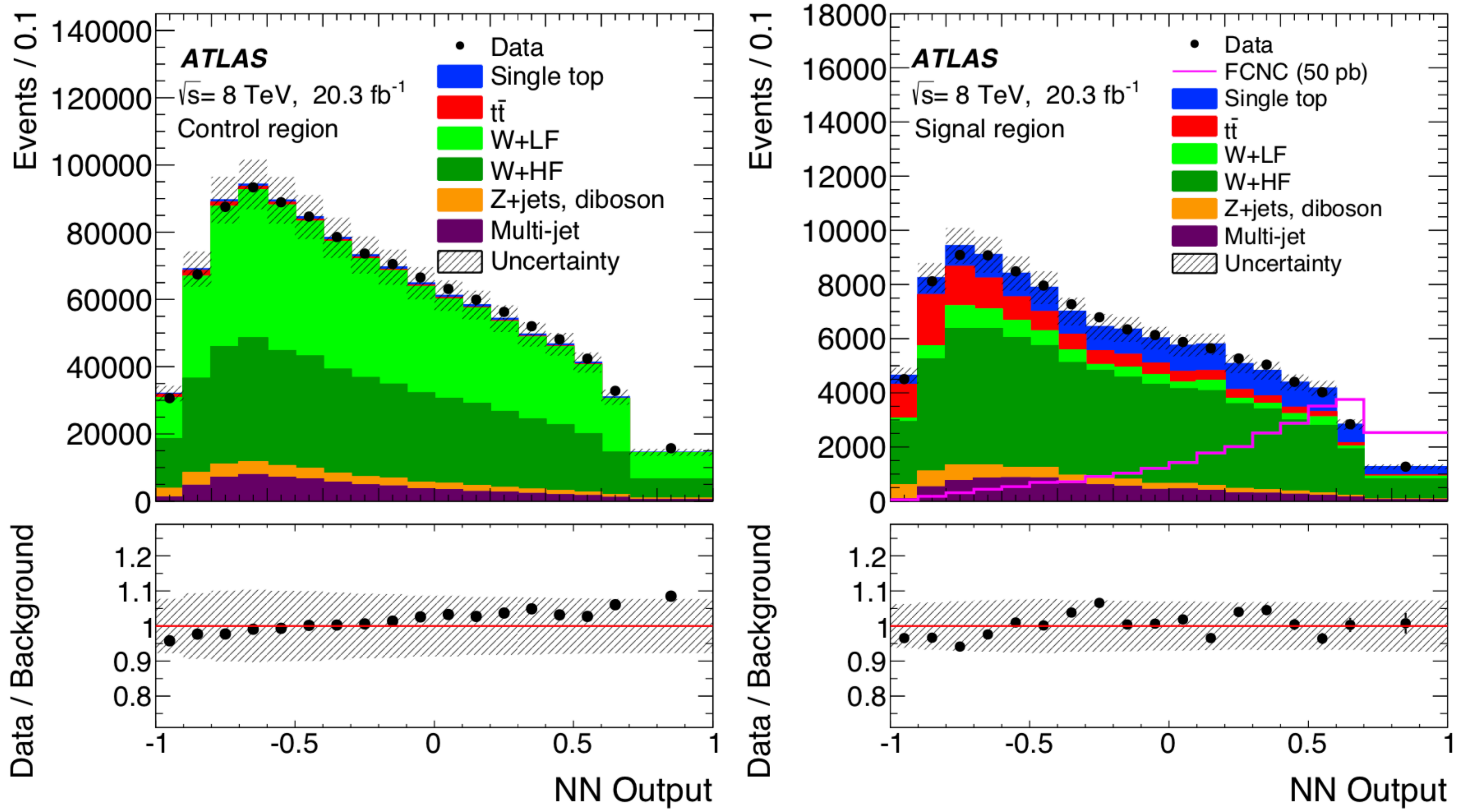






$t \to gq$

$$gq \to t \to W(\to \ell\nu)b$$



	Expected	Observed
t —> gu	0.35×10^{-4}	0.4×10^{-4}
t —> gc	1.8×10^{-4}	2.0×10^{-4}

$t \to gq$

$gq \to t \to W(\to \ell\nu)b$

- upper limits at the production **cross section** multiplied by $\mathscr{B}(t \to Wb)$:

$$\sigma_{gq\to t} \times \mathscr{B}(t \to Wb) < 3.4(2.9)\text{pb}$$

- upper limits on the **coupling constants** of the FCNC interactions divided by the scale of new physics Λ:

$$\kappa_{ugt}/\Lambda < 5.8 \times 10^{-3}\text{TeV}^{-1} \quad \text{and} \quad \kappa_{cgt}/\Lambda < 13 \times 10^{-3}\text{TeV}^{-1}$$

- upper limits on the $\mathscr{B}$ using $\mathscr{B}(t \to qg) = C(\kappa_{qgt}/\Lambda)^2$:

$$\mathscr{B}(t \to gu) < 0.4(0.35) \times 10^{-4} \quad \text{and} \quad \mathscr{B}(t \to gc) < 2.0(1.8) \times 10^{-4}$$