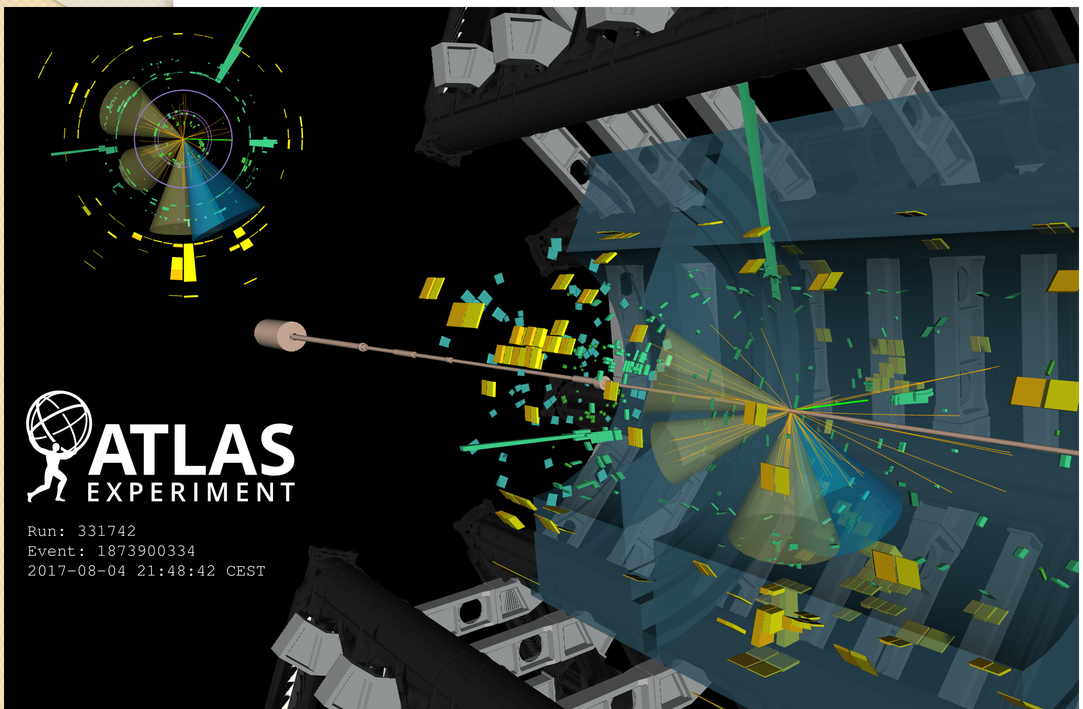
Measurements of Higgs boson production in association with top quarks at the ATLAS experiment



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on behalf of the ATLAS collaboration

EPS-HEP 2023 Hamburg
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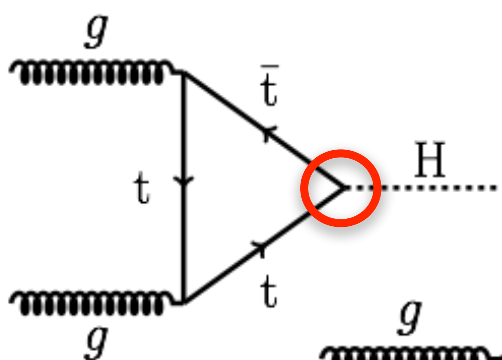
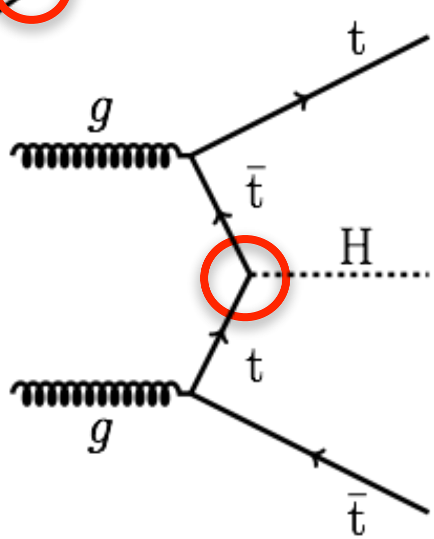
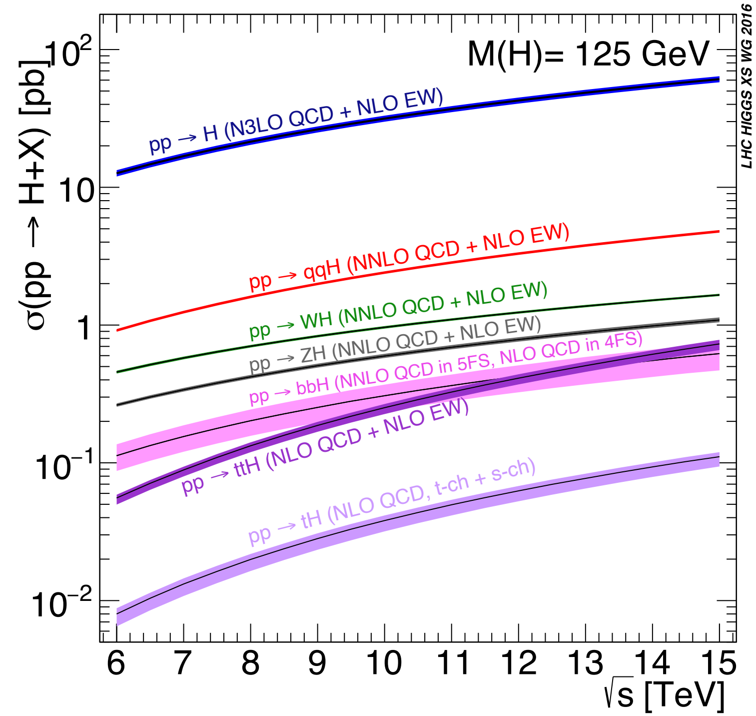
Motivation

- In SM, top-Higgs coupling (y_t) **very large wrt other fermions:** good opportunity to study Higgs Yukawa couplings to fermions
- Access to $\kappa_t = y_t / y_t(SM)$ with **ggF + H→$\gamma\gamma$ decay**
- **Model-dependent constraints on κ_t**, assuming no BSM particles in the loop



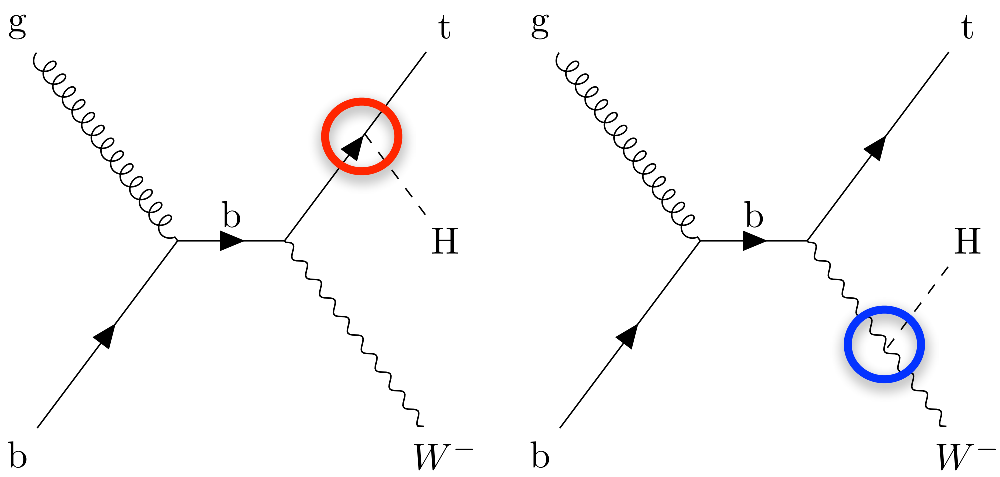
- **ttH + tH => direct probes to study y_t**





- **Small cross-section for ttH (0.5 fb, ~1% ggF)**
- **Single top + Higgs cross-section even one order of magnitude lower than ttH:** very challenging SM process to observe...

Motivation



- **Single-top + Higgs production** involves **interfering diagrams** with **top-Higgs** and **W-Higgs couplings**

- **In SM destructive interference** but if $\kappa_t=-1$ **tH cross-section can be enhanced** by one order of magnitude

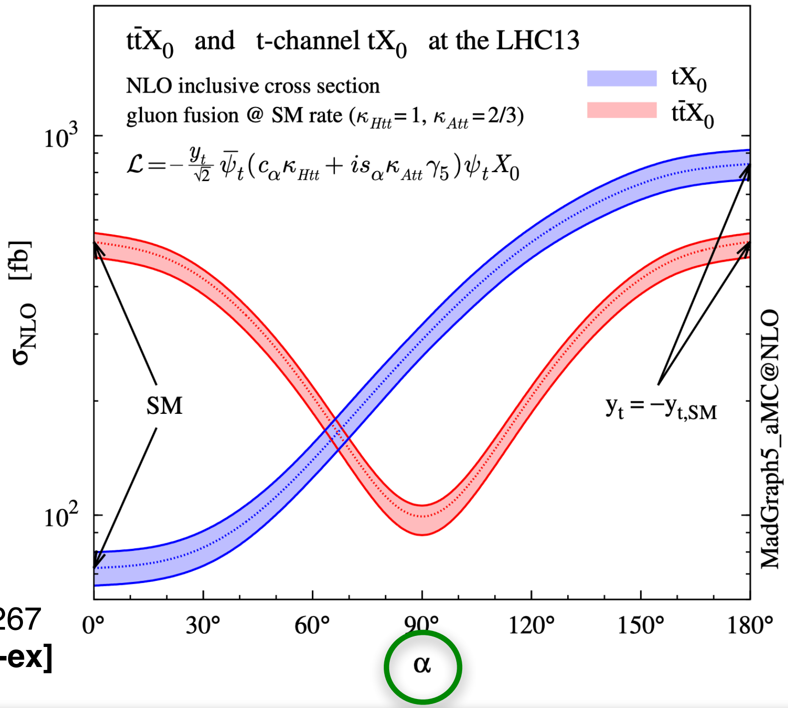
$$\mathcal{L}_{t\bar{t}H} = -\kappa_t y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

- **CP-structure of top-Higgs coupling** (mixing angle α) can also be probed

  => impact both cross-section + kinematics

- **Combined analysis of ttH + tH processes** can be used to constrain κ_t and α

- For more Higgs CP-related measurements see C. Grefe's talk

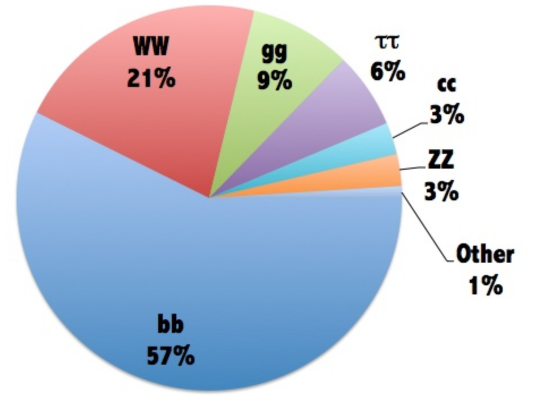


Eur. Phys. J. C 75 (2015) 6, 267
arXiv:1504.00611 [hep-ex]

Strategy

- **Target as many decay modes as possible** for top + Higgs to maximise sensitivity

- **ttH + tH H→bb channel**
  Largest branching ratio
  Low S/B + combinatorics
  Large theoretical uncertainties on irreducible tt+bb background



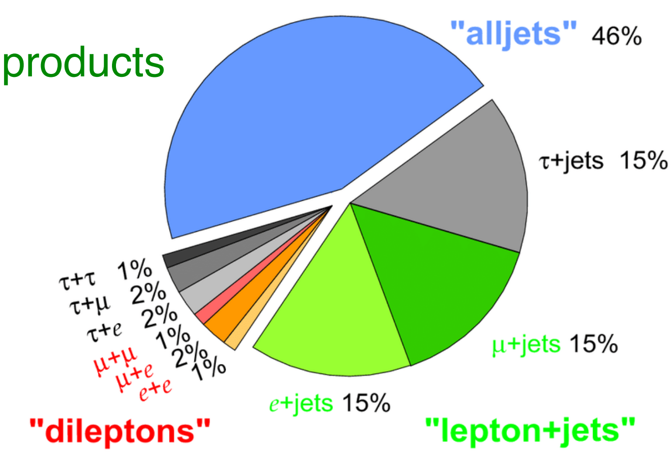
- **ttH + tH H→WW / ZZ / $\tau\tau$ multilepton channels**
  Clean final state with leptons
  Low irreducible backgrounds (S/B~1)
  Challenging reducible backgrounds w/ non-prompt leptons + jets faking τ_h

Higgs BR

Top pair BR

- **ttH + tH H→$\gamma\gamma$ channel**
  Very clean signature, possible to reconstruct all Higgs decay products
  Good S/B
  Low branching ratio

- Other subdominant channels also covered in other analyses: H→ZZ→4l, H→ $\tau_h\tau_h$…

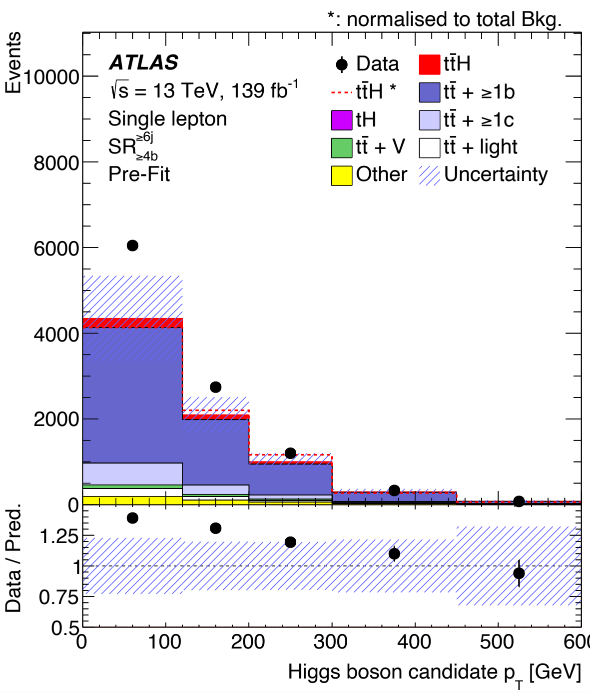


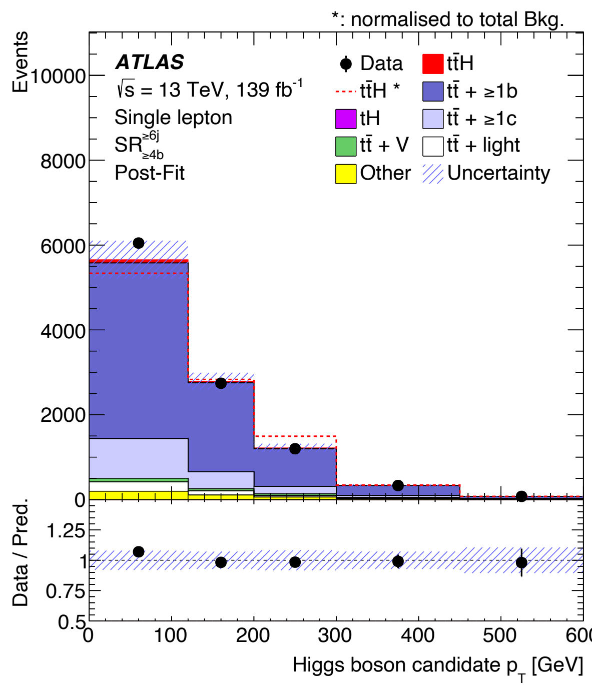
Cross-section and STXS measurements

ttH H→bb

- **Dilepton + single lepton resolved + boosted channels:** dominated by tt+heavy flavour background
- **BDTs + DNN used for:**
  - jet-parton assignment
  - signal extraction

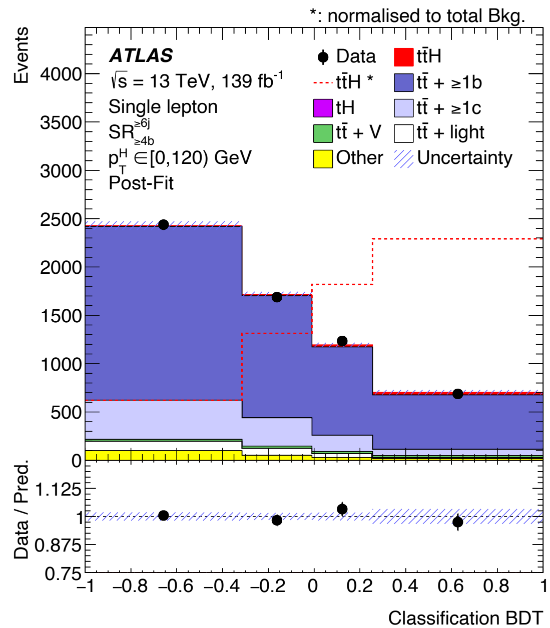
Region		Dilepton				Single-lepton			
		$\mathrm{SR}^{\geq 4j}_{\geq 4b}$	$\mathrm{CR}^{\geq 4j}_{3b\ \mathrm{hi}}$	$\mathrm{CR}^{\geq 4j}_{3b\ \mathrm{lo}}$	$\mathrm{CR}^{3j}_{3b\ \mathrm{hi}}$	$\mathrm{SR}^{\geq 6j}_{\geq 4b}$	$\mathrm{CR}^{5j}_{\geq 4b\ \mathrm{hi}}$	$\mathrm{CR}^{5j}_{\geq 4b\ \mathrm{lo}}$	$\mathrm{SR}_{\mathrm{boosted}}$
#leptons		$= 2$				$= 1$			
#jets		≥ 4			$= 3$	≥ 6	$= 5$		≥ 4
#b-tag	@85%	–				≥ 4			
	@77%	–				–			$\geq 2^{\dagger}$
	@70%	≥ 4	$= 3$			≥ 4			–
	@60%	–	$= 3$	< 3	$= 3$	–	≥ 4	< 4	–
#boosted cand.		–				0			≥ 1
Fit input		BDT	Yield			BDT/Yield	$\Delta R^{\mathrm{avg}}_{bb}$		BDT

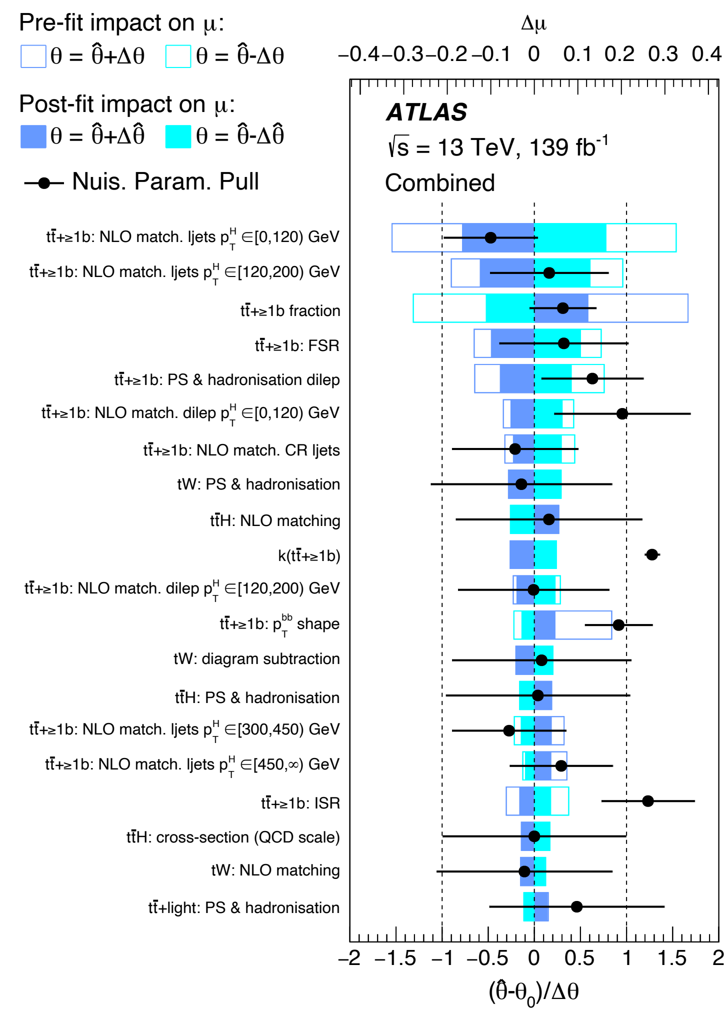


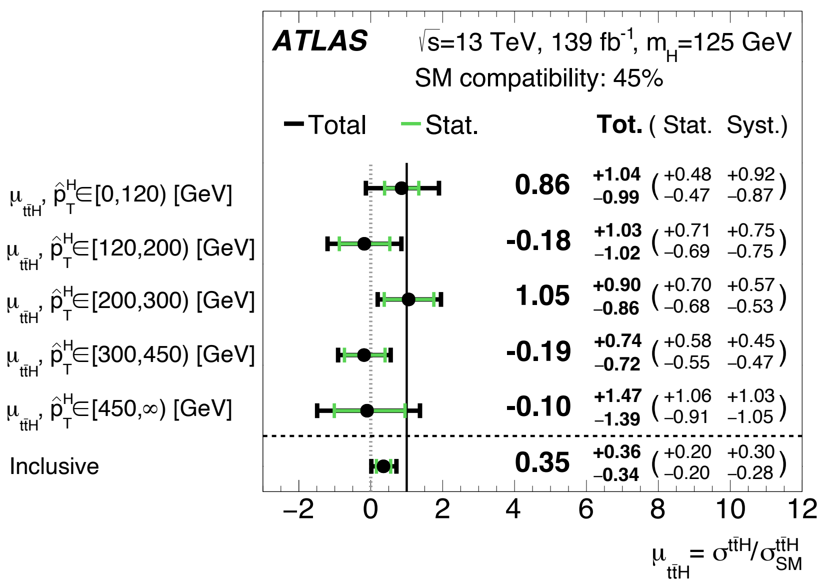


- **tt+bb background** modelled with **4FS NLO** simulation with extra b-jets from ME + **free-floating normalisation**
  k(tt+bb)=1.26 ± 0.09
- **Ad-hoc uncertainty** derived from inclusive signal region used to cover for **reco p_T(H) mismodelling in background**

- Good post-fit agreement observed, with **uncertainty dominated by tt+hf modelling systematics**
- **Sensitivity:** 1.0σ observed (2.7σ expected)

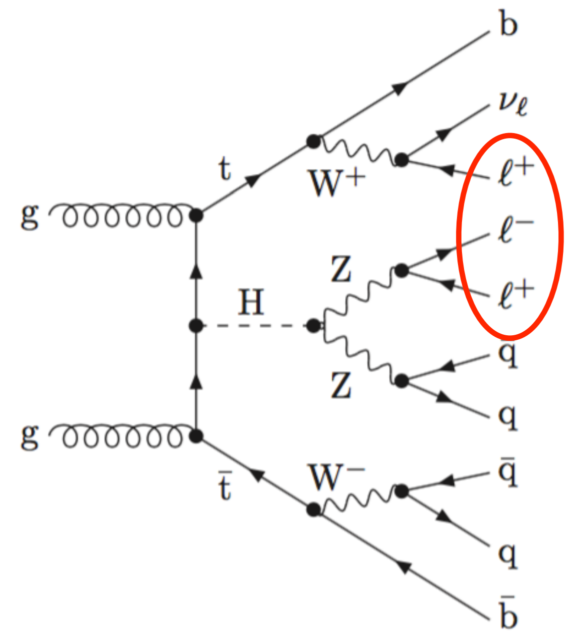




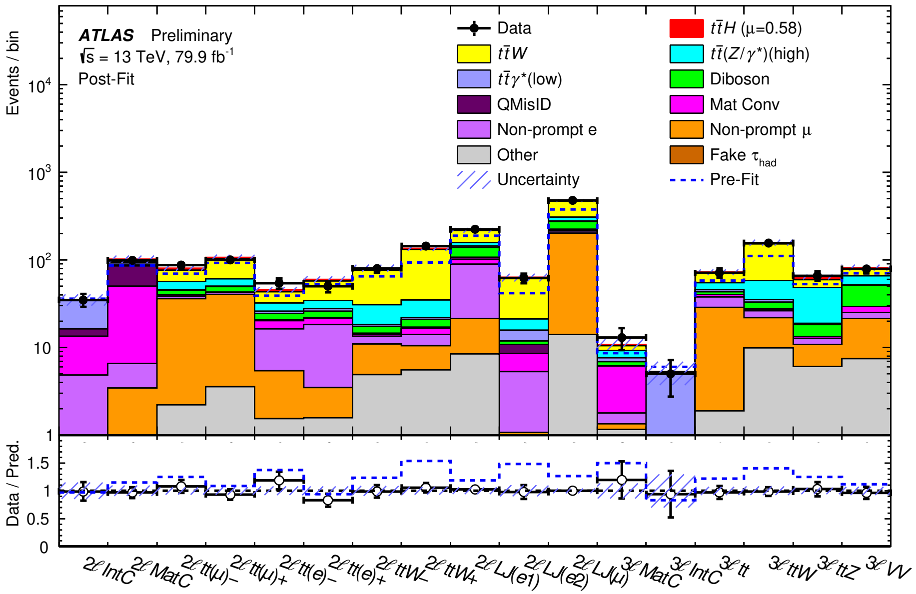


- **Sensitivity beyond pT=300 GeV thanks to boosted categories**

- **Targets final-state with several leptons + τ_h**
- **Main sources of background:**
  - **irreducible:** ttV, di-boson
  - **reducible:** non-prompt leptons, fake τ_h, photon conversions, charge mis-ID



- MVA selections used to separate **prompt leptons** (from W/Z/**τ** decays) from **non-prompt leptons** (b decays, light hadrons)



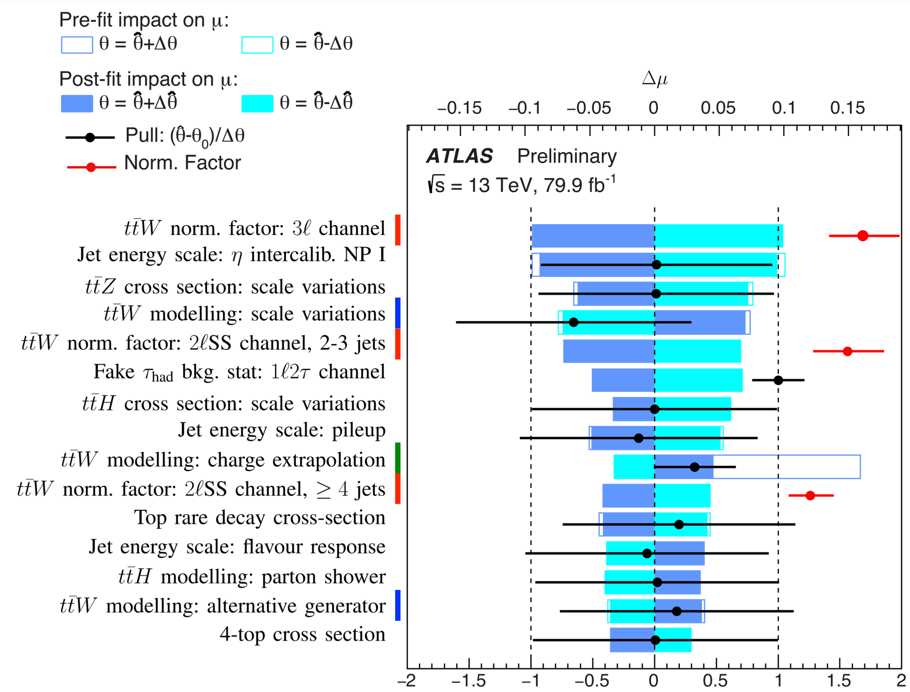
- Subcategories based on lepton charge + flavour + b-jet multiplicity
- **Background modelling:**
  - simulation for shape
  - control regions for normalisation
- **BDTs used for signal extraction:** multi-dimensional binning w/ binary classifiers or multi-classifiers

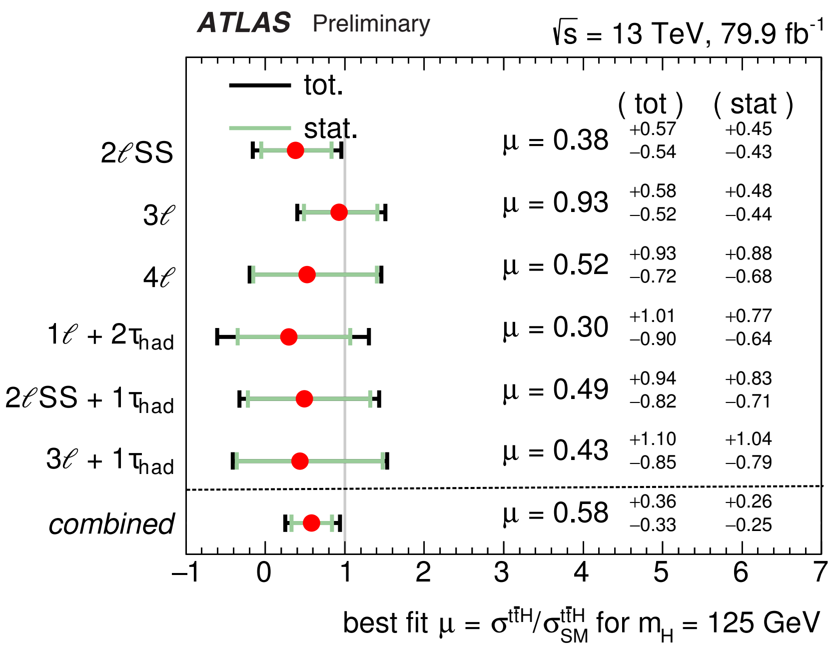
ttH multilepton

ATLAS-CONF-2019-045

- **Challenging modelling of ttW background:**
  - several uncorrelated free-floating normalisations factors
  - theoretical uncertainties
  - ad hoc extrapolation uncertainties for charge asymmetry + b-jet multiplicity

=> recent dedicated ttW measurements will help improving those (see R. Ospanov's talk)





- **Observed excess in ttW** taking into account state-of-the-art QCD and EW corrections (σ(ttW)=727 fb)
- **Systematic uncertainties getting larger than stat. uncertainty:** dominated by ttW modelling + jet energy scale
- **Sensitivity:** 1.8σ observed (3.1σ expected)

ttH + tH H→γγ

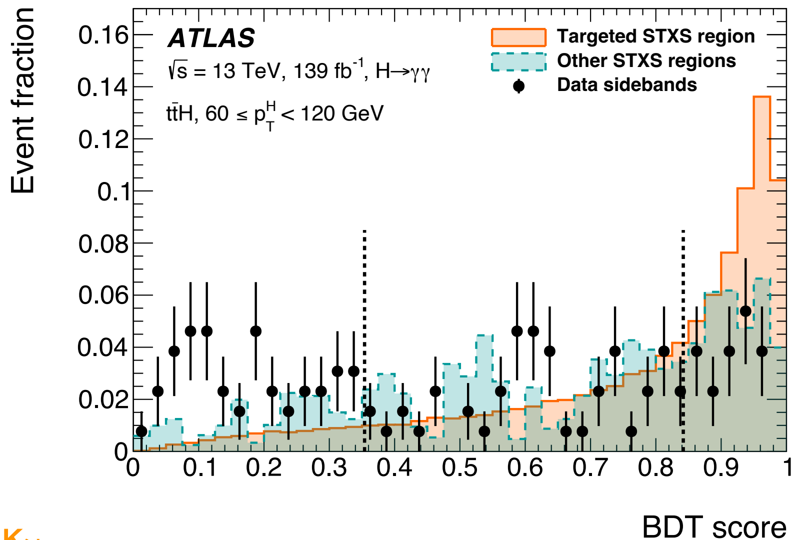
[HIGG-2020-16](#)
[JHEP 07 (2023) 088](#)

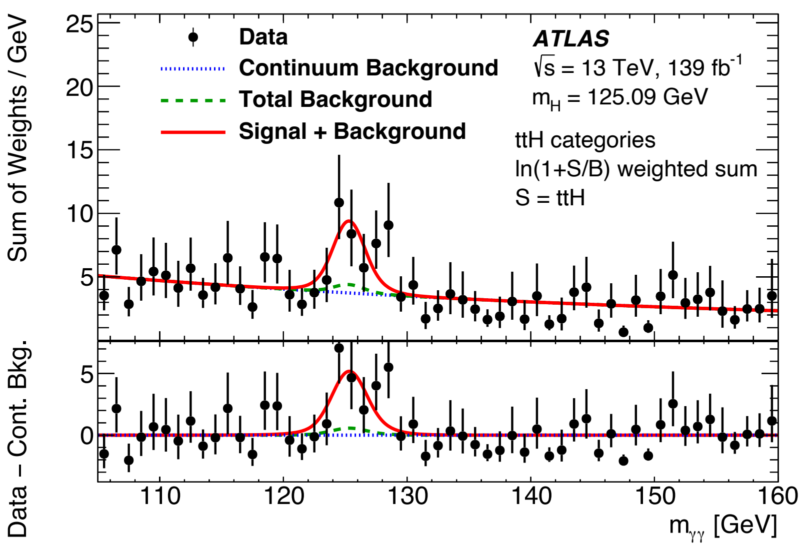
- **Part of inclusive H->γγ STXS measurements:**
  - **STXS bin assignment** handled w/ multi-classifier BDT
  - **subcategories with increasing purity** defined with signal vs background BDT

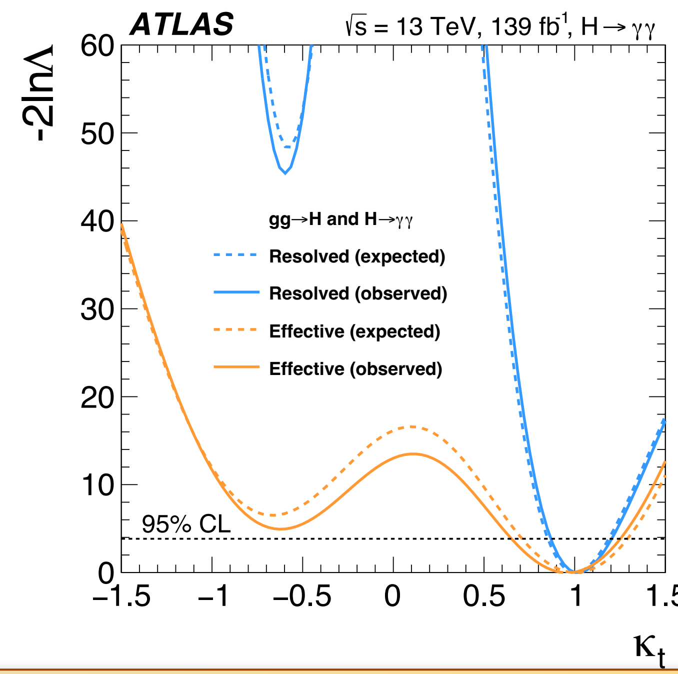
  => fit of m(γγ) for signal extraction

- **tH categories** split between categories optimised for tHW / tHq κ_t =1 (SM) / tHq κ_t=-1 (BSM)

- STXS measurements performed + κ_t measurement: **κ_t<0 excluded at 2.2σ** with effective κ_g and κ_γ, **sensitivity from tH categories**

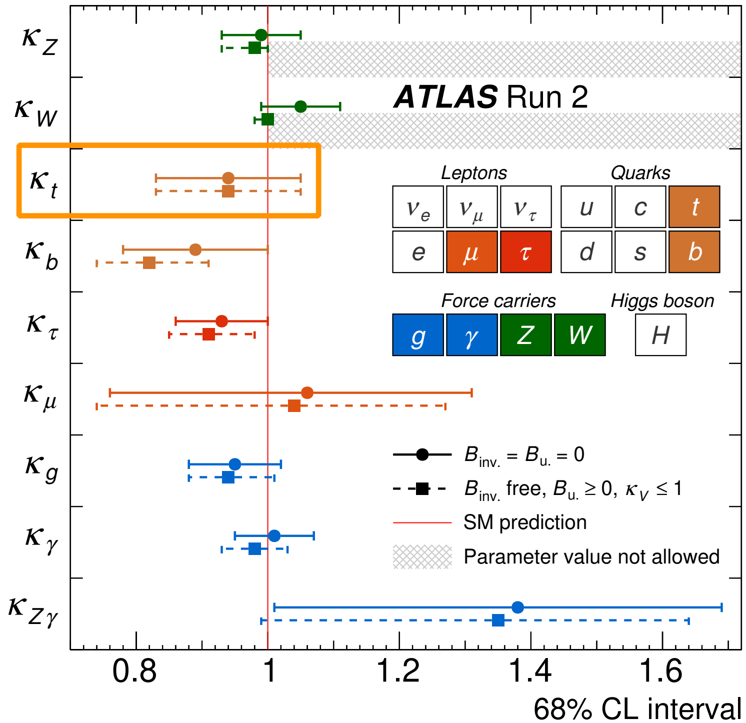






Higgs combination

[HIGG-2021-23](#)
[Nature 607 (2022)](#)



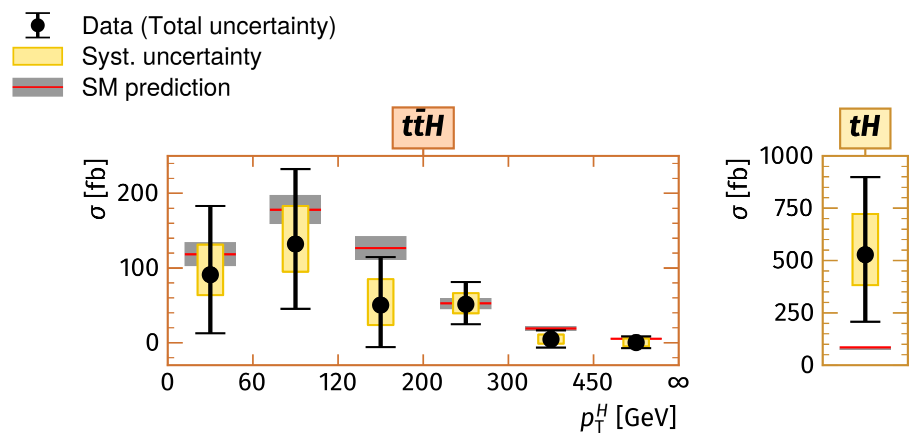
- **Combination of all Run 2 Higgs analyses:** inclusive cross-section + STXS measurements
- **Combined ttH + tH sensitivity 6.4σ** (exp. 6.6σ)
- **Sensitivity to κ_t from ttH categories** (under hypothesis with independent effective κ_g and κ_γ)

  κ_t = 0.94 ± 0.11 under $B_{inv}=B_u=0$ hypothesis
- **Complementary between different channels exploited for STXS measurement**

- **Separate tH measurement** possible thanks to tH, $H\rightarrow\gamma\gamma$ categories

  σ(tH) < 15x SM @ 95% CL (7x exp.)

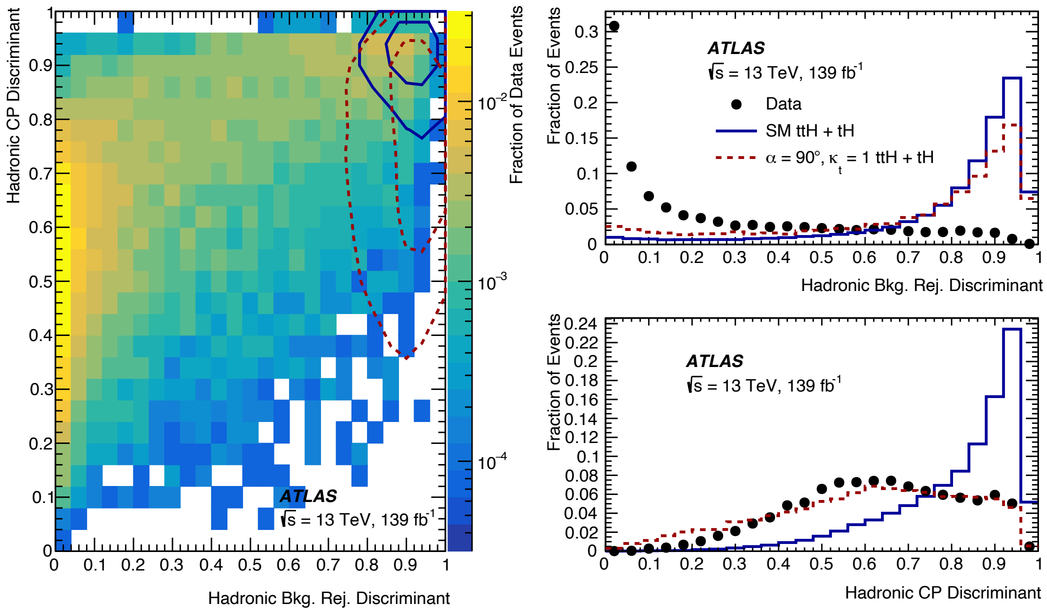
- **Large ttH vs tH correlation -56%**: improved in the future thanks to **dedicated tH analyses for all channels**



Top Yukawa CP properties

ttH + tH H→γγ

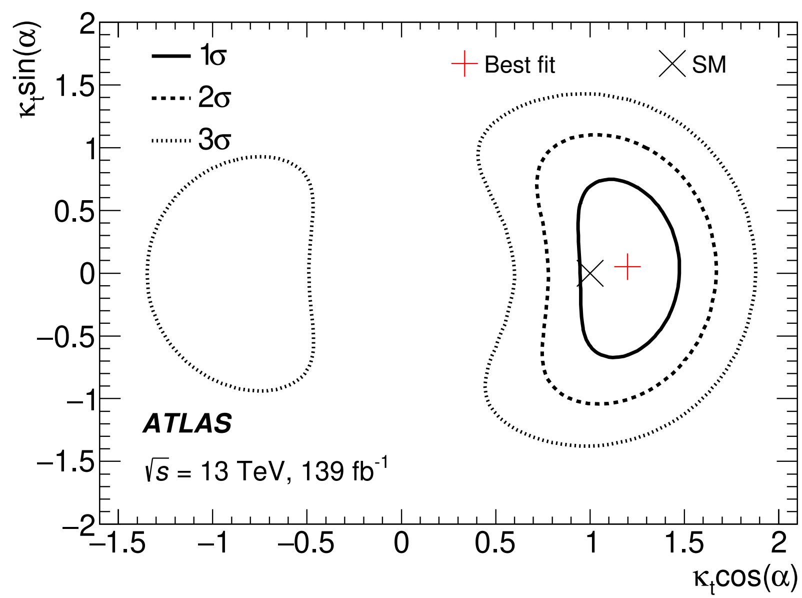
[HIGG-2019-01](#) [Phys. Rev. Lett. 125 (2020) 061802](#)



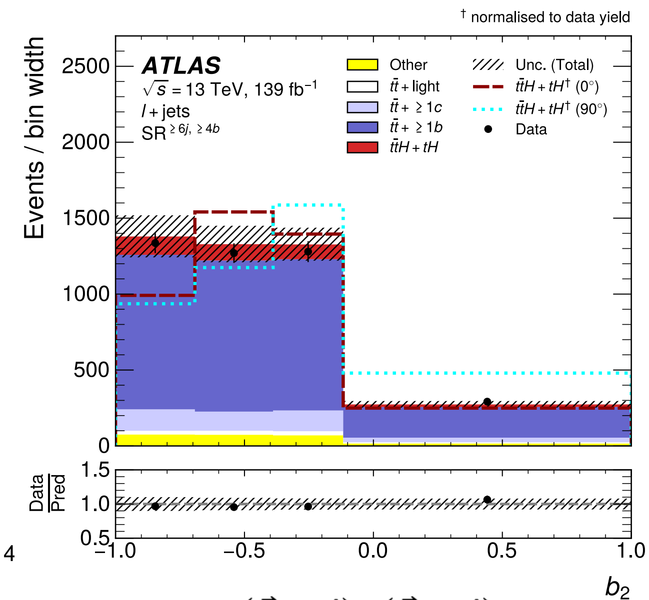
- **Similar analysis strategy as for SM ttH + tH H→γγ analysis**
- 2D categories based on **sig. vs bkg BDT + CP-even vs CP-odd signal** exploiting:
  - top reco. BDT for jet assignment
  - angular + kinematic variables related to reconstructed tops + Higgs

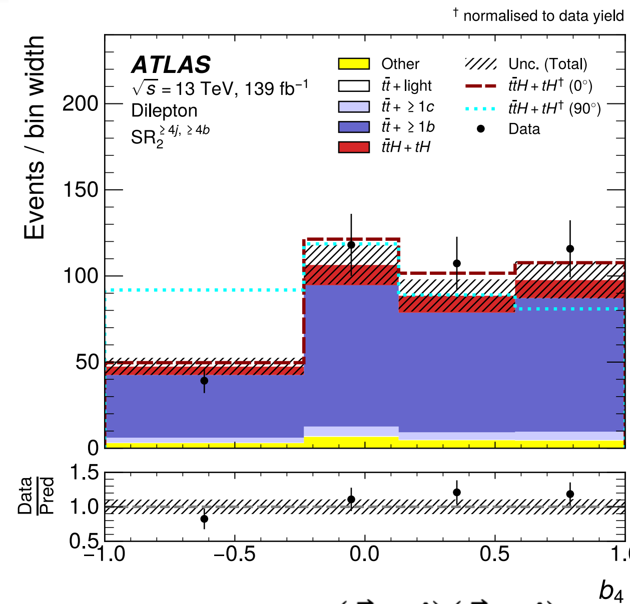
- **Measurement of $\kappa_t \cos(\alpha)$ - $\kappa_t \sin(\alpha)$** with κ_g and κ_γ inputs from Higgs coupling combination w/o ttH + tH channels

- **Results:**
  - |α|>43° excluded at 95% CL
  - Inverted top coupling hypothesis (α=180°) excluded at 2.5σ
  - Pure CP-odd hypothesis (α=90°) excluded at 3.9σ



- **Similar analysis strategy as SM ttH→bb measurement** for event categorisation + background estimation

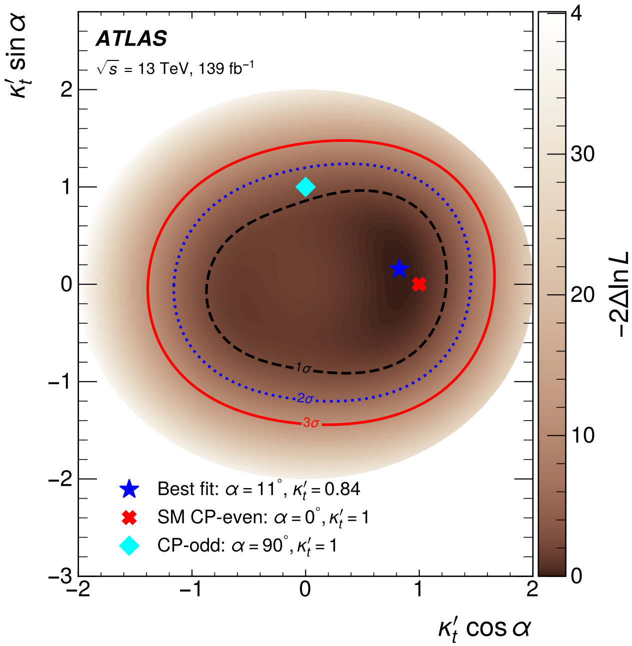




$$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

p1, p2 = 4-momenta top quarks
$\hat{z}$ = beam-axis

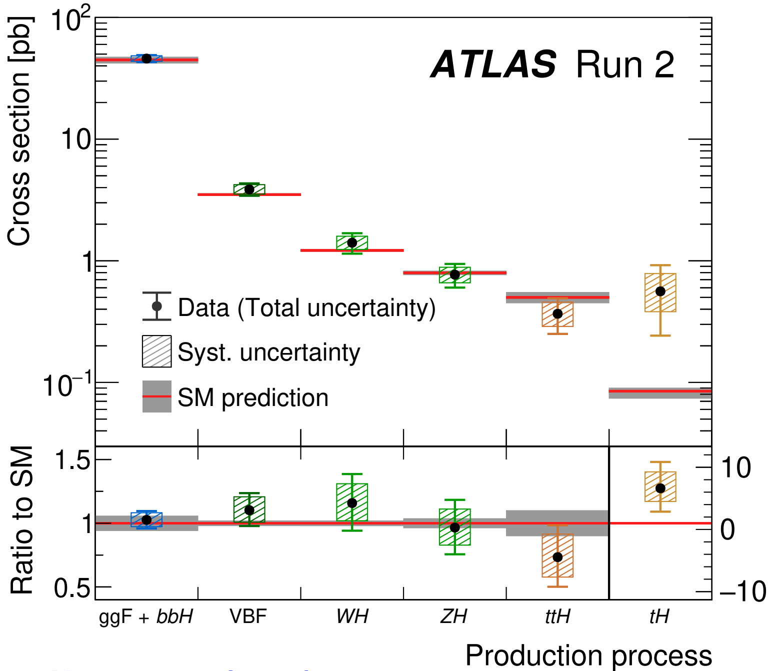
$$b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$



- 2D categories built on top based on **sig. vs bkg BDT + angular variables b_2 / b_4**

- **Results:**
  - Best fit $\alpha=11^{\circ}{}^{+52^{\circ}}_{-73^{\circ}}$ and $\kappa_t=0.84^{+0.30}_{-0.46}$
  - Pure CP-odd hypothesis (α=90°) excluded at 1.2σ

Conclusion



[Nature 607 (2022)](#)

- **Full Run 2 dataset has allowed to firmly confirm observation of ttH production mode**
- **Opens the way for more detailed studies beyond inclusive cross-section measurements:**
  - differential STXS measurements
  - studies of CP properties of top Yukawa
  - search for rare tH process

- **Background modelling very challenging** for some channels (tt+bb, ttW)
  => ttH analyses prompted studies leading to **dedicated measurements, improving their predictions**

- Some channels still statistically limited + new analysis strategies to explore so **large room for improvement with Run 3 dataset currently collected**

Back-up

ttH H→bb

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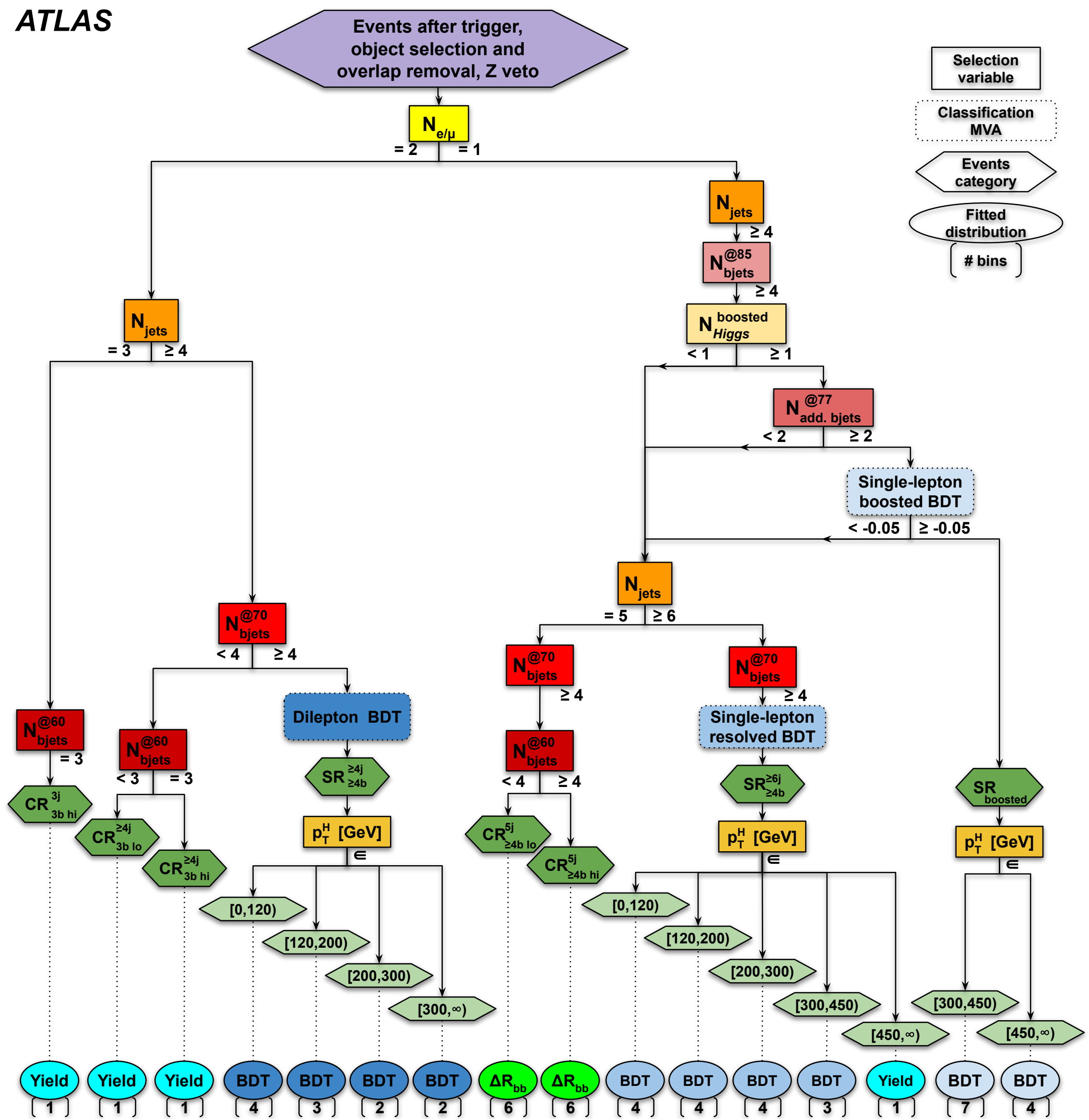

ttH H→bb

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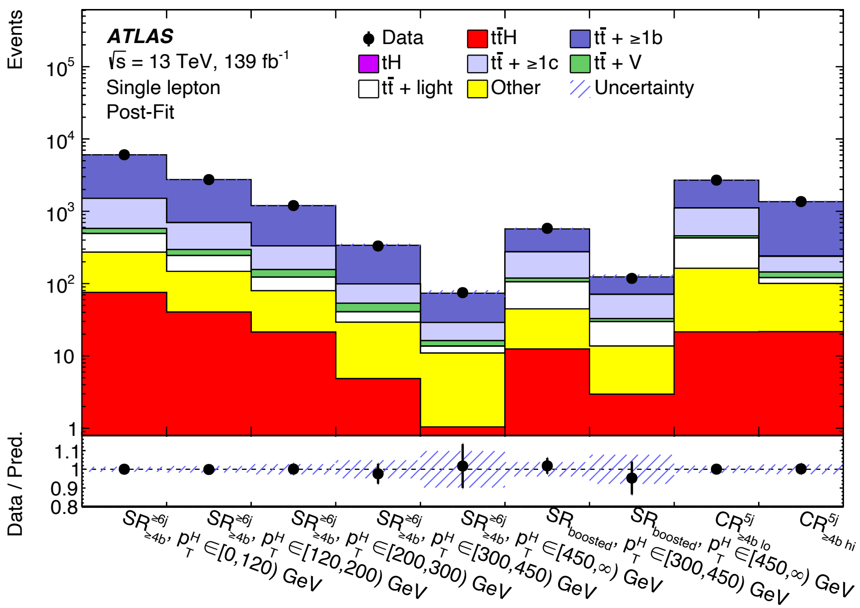
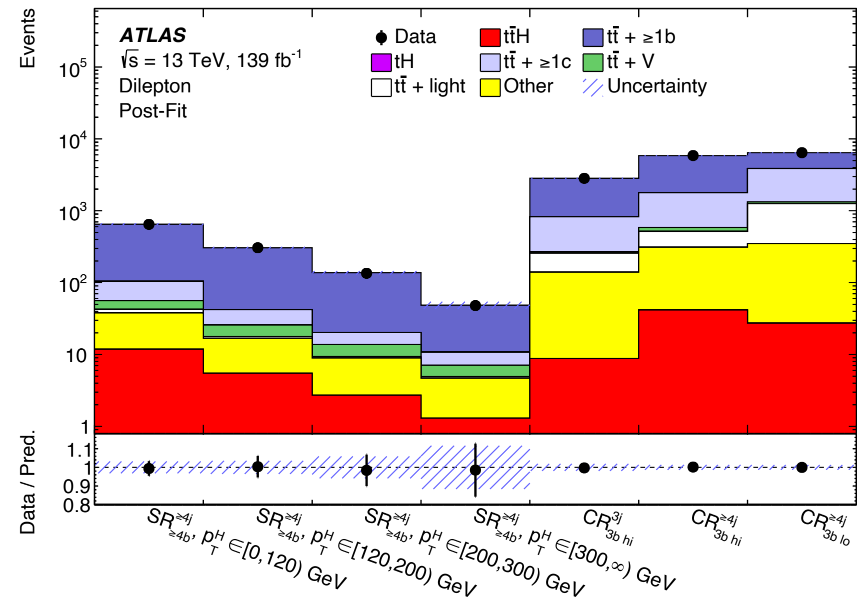
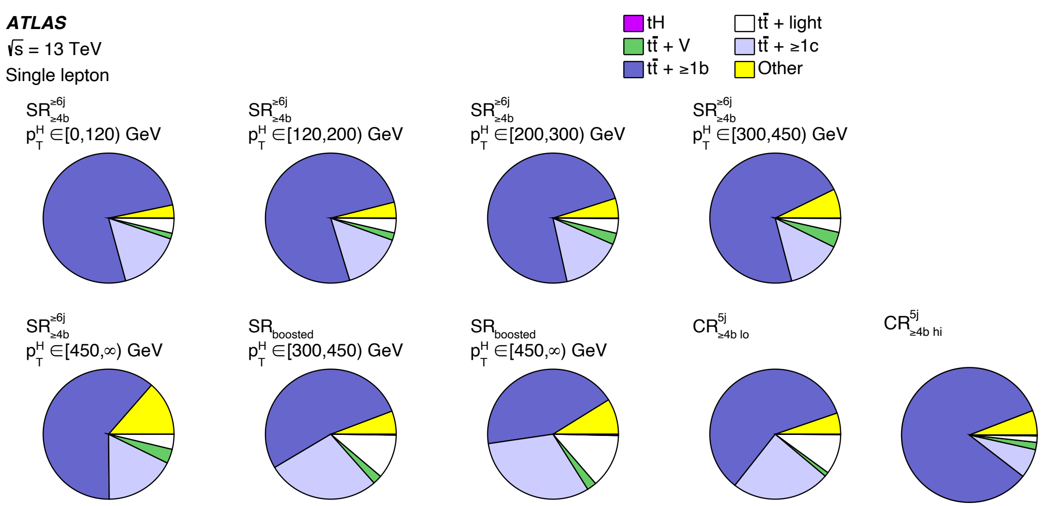
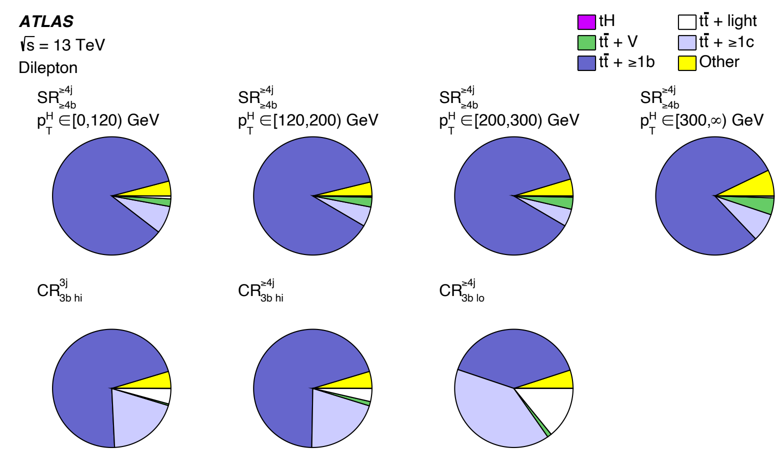
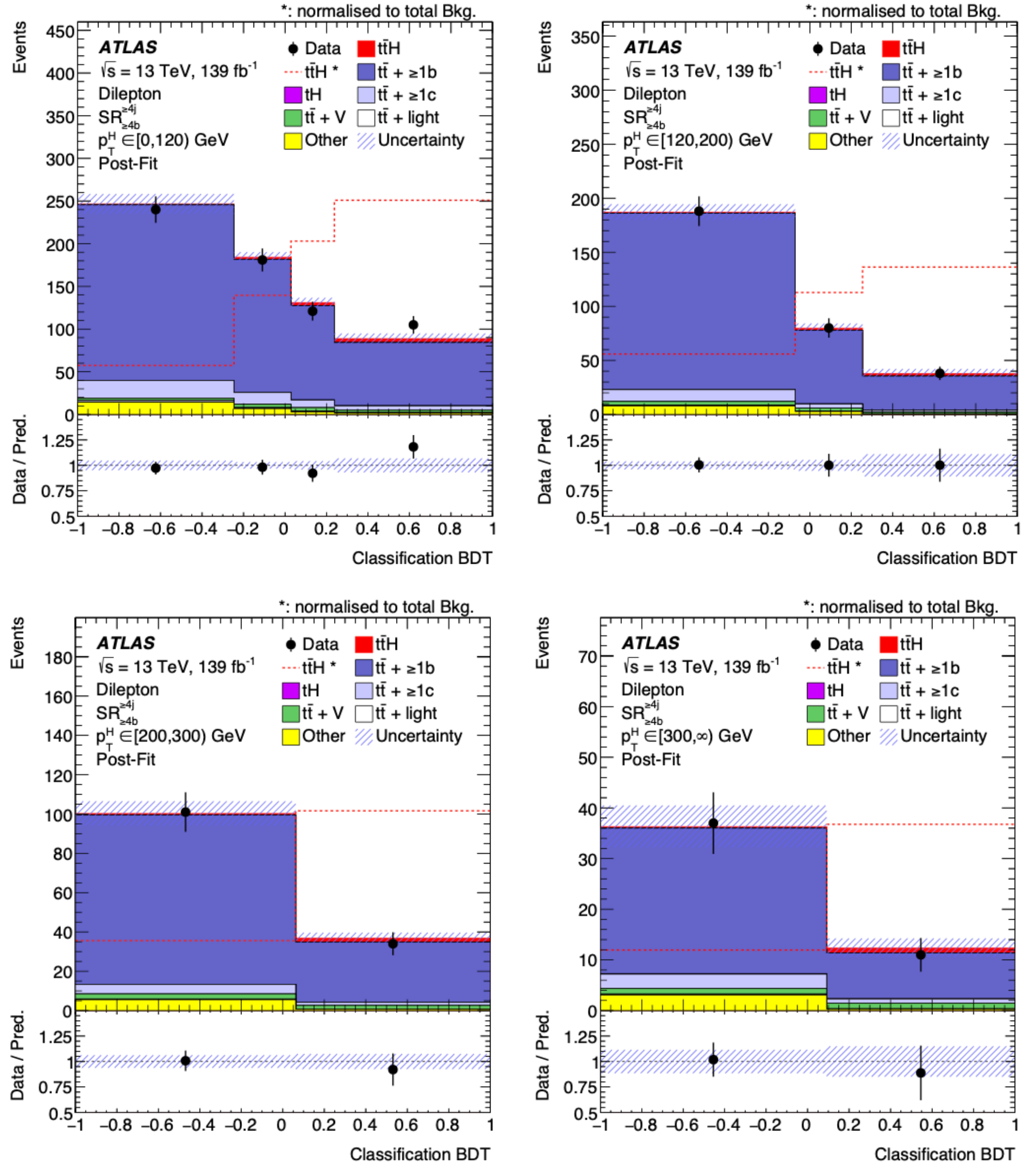




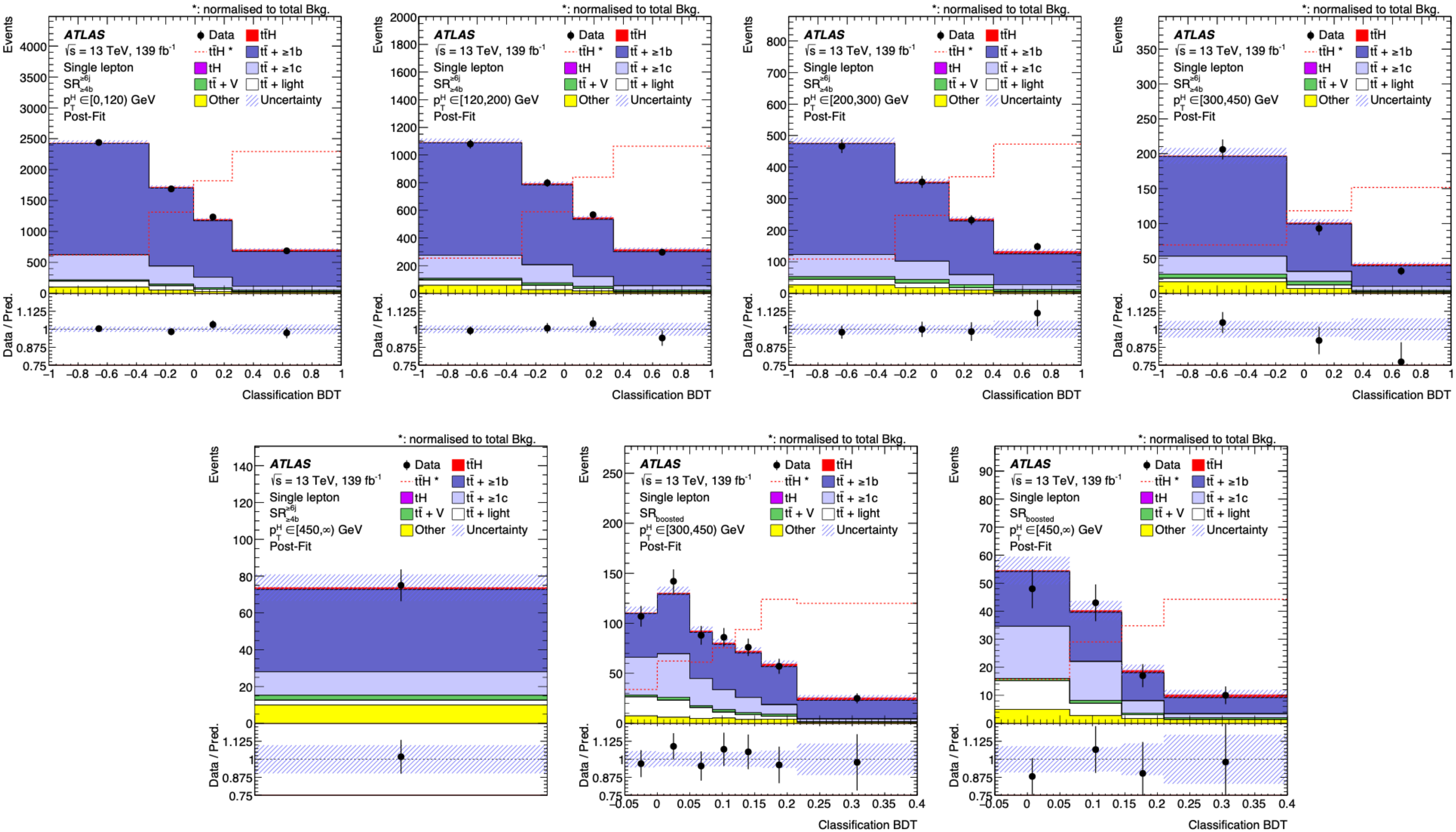


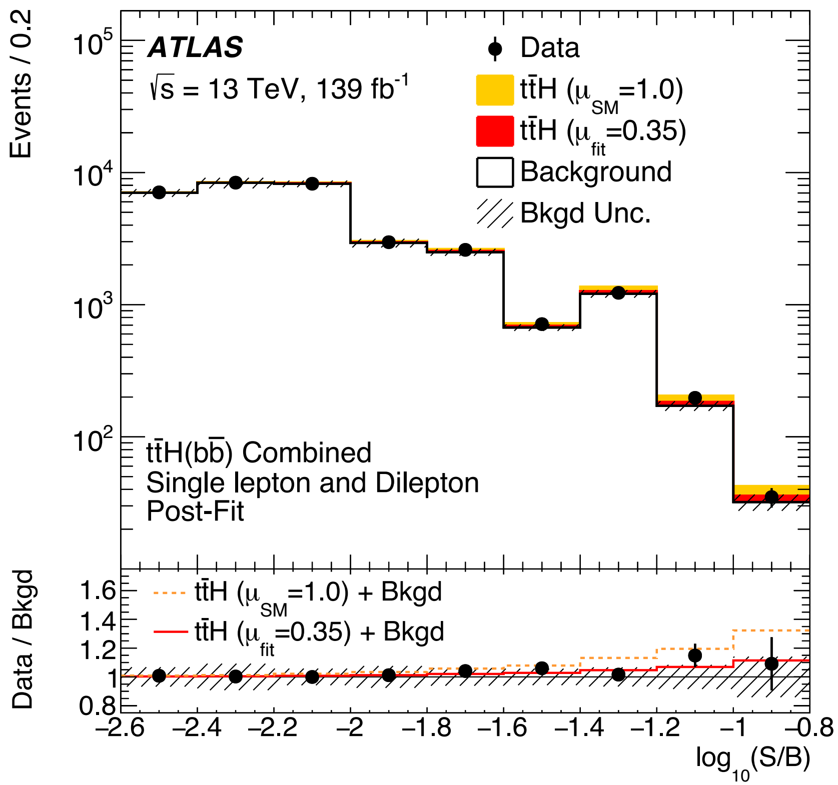


- **Dilepton BDT distributions**

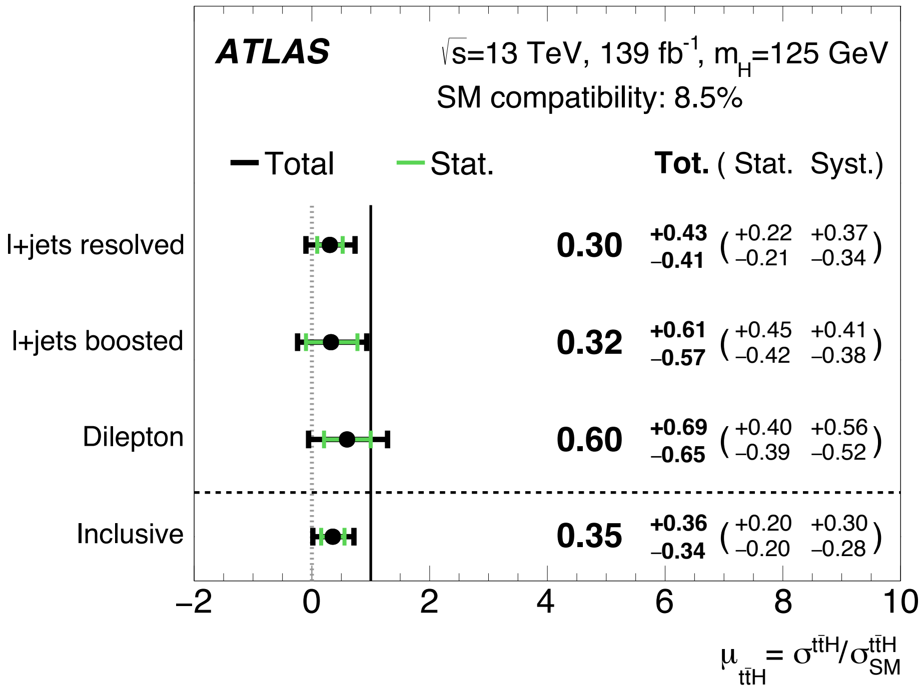


- **Single-lepton BDT distributions**





ATLAS
√s = 13 TeV, 139 fb-1
Data
tt̄H (μSM=1.0)
tt̄H (μfit=0.35)
Background
Bkgd Unc.
tt̄H(bb̄) Combined
Single lepton and Dilepton
Post-Fit
Events / 0.2
tt̄H (μSM=1.0) + Bkgd
tt̄H (μfit=0.35) + Bkgd
Data / Bkgd
log10(S/B)



ATLAS
√s=13 TeV, 139 fb-1, mH=125 GeV
SM compatibility: 8.5%
Total
Stat.
Tot. (Stat. Syst.)
l+jets resolved
0.30 +0.43 −0.41 (+0.22 −0.21 +0.37 −0.34)
l+jets boosted
0.32 +0.61 −0.57 (+0.45 −0.42 +0.41 −0.38)
Dilepton
0.60 +0.69 −0.65 (+0.40 −0.39 +0.56 −0.52)
Inclusive
0.35 +0.36 −0.34 (+0.20 −0.20 +0.30 −0.28)
μtt̄H = σtt̄H/σtt̄H SM

- **ttbar samples + systematics**

$t\bar{t}$ + jets and single-top

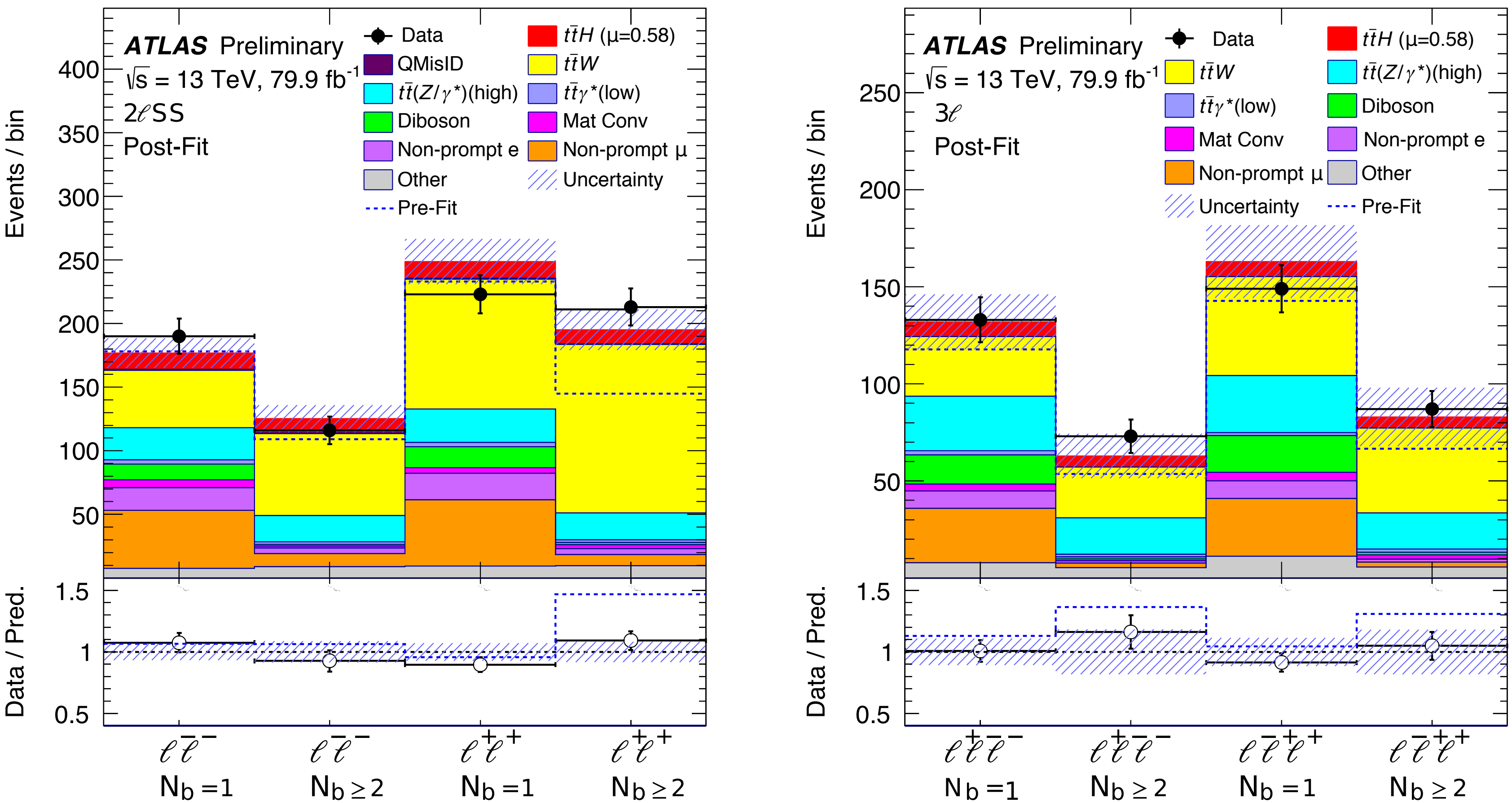
$t\bar{t}$	Powheg Box v2	NNPDF3.0nlo	Pythia 8.230	NNLO+NNLL [45,46,47,48,49,50,51]
	Powheg Box v2	NNPDF3.0nlo	Herwig 7.04	NNLO+NNLL [45,46,47,48,49,50,51]
	MadGraph5_aMC@NLO 2.6.0	NNPDF3.0nlo	Pythia 8.230	NNLO+NNLL [45,46,47,48,49,50,51]
$t\bar{t}+b\bar{b}$	Powheg Box Res	NNPDF3.0nlo nf4	Pythia 8.230	–
	Sherpa 2.2.1	NNPDF3.0nnlo nf4	Sherpa	–
tW	Powheg Box v2 [DR]	NNPDF3.0nlo	Pythia 8.230	NLO+NNLL [52,53]
	Powheg Box v2 [DS]	NNPDF3.0nlo	Pythia 8.230	NLO+NNLL [52,53]
	Powheg Box v2 [DR]	NNPDF3.0nlo	Herwig 7.04	NLO+NNLL [52,53]
	MadGraph5_aMC@NLO 2.6.2 [DR]	CT10nlo	Pythia 8.230	NLO+NNLL [52,53]
t-channel	Powheg Box v2	NNPDF3.0nlo nf4	Pythia 8.230	NLO [54,55]
	Powheg Box v2	NNPDF3.0nlo nf4	Herwig 7.04	NLO [54,55]
	MadGraph5_aMC@NLO 2.6.2	NNPDF3.0nlo nf4	Pythia 8.230	NLO [54,55]
s-channel	Powheg Box v2	NNPDF3.0nlo	Pythia 8.230	NLO [54,55]
	Powheg Box v2	NNPDF3.0nlo	Herwig 7.04	NLO [54,55]
	MadGraph5_aMC@NLO 2.6.2	NNPDF3.0nlo	Pythia 8.230	NLO [54,55]

Uncertainty source	Description		Components
$t\bar{t}$ cross-section	±6%		$t\bar{t}$ + light
$t\bar{t}+\geq 1b$ normalisation	Free-floating		$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1c$ normalisation	±100%		$t\bar{t}+\geq 1c$
NLO matching	MadGraph5_aMC@NLO + Pythia 8 vs Powheg Box + Pythia 8		All
PS & hadronisation	Powheg Box + Herwig 7 vs Powheg Box + Pythia 8		All
ISR	Varying α_s^{ISR} (PS), μ_r & μ_f (ME)	in Powheg Box Res + Pythia 8	$t\bar{t}+\geq 1b$
		in Powheg Box + Pythia 8	$t\bar{t}+\geq 1c$, $t\bar{t}$ + light
FSR	Varying α_s^{FSR} (PS)	in Powheg Box Res + Pythia 8	$t\bar{t}+\geq 1b$
		in Powheg Box + Pythia 8	$t\bar{t}+\geq 1c$, $t\bar{t}$ + light
$t\bar{t}+\geq 1b$ fractions	Powheg Box + Herwig 7 vs Powheg Box + Pythia 8		$t\bar{t}+1b$, $t\bar{t}+\geq 2b$
p_T^{bb} shape	Shape mismodelling measured from data		$t\bar{t}+\geq 1b$

ttH multilepton

Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$
2ℓSS	Two same-charge (SS) very tight (T*) leptons, $p_{\text{T}} > 20$ GeV No τ_{had} candidates $m(\ell^+\ell^-) > 12$ GeV for all SF pairs **13 categories**: enriched with $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}$, mat. conv, int. conv., split by lepton flavour, charge, jet and b-jet multiplicity
3ℓ	Three loose (L) leptons with $p_{\text{T}} > 10$ GeV; sum of light-lepton charges $= \pm 1$ Two SS very tight (T*) leptons, $p_{\text{T}} > 15$ GeV One OS (w.r.t the SS pair) loose-isolated (L*) lepton, $p_{\text{T}} > 10$ GeV No τ_{had} candidates $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2 \text{ GeV}\rvert > 10$ GeV for all SFOS pairs $\lvert m(3\ell) - 91.2 \text{ GeV}\rvert > 10$ GeV **7 categories**: enriched with $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, VV, $t\bar{t}$, mat. conv, int. conv
4ℓ	Four loose-isolated (L*) leptons; sum of light lepton charges $= 0$ $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2 \text{ GeV}\rvert > 10$ GeV for all SFOS pairs $m(4\ell) < 115$ GeV or $m(4\ell) > 130$ GeV **2 categories**: Zenr (Z-enriched;1 or 2 SFOS pairs) or Zdep (Z-depleted; 0 SFOS pairs)
$1\ell 2\tau_{\text{had}}$	One tight (T) lepton, $p_{\text{T}} > 27$ GeV Two OS τ_{had} candidates At least one tight τ_{had} candidate $N_{\text{jets}} \geq 3$
$2\ell\text{SS}1\tau_{\text{had}}$	2ℓSS selection, except: One medium τ_{had} candidate $N_{\text{jets}} \geq 4$
$3\ell 1\tau_{\text{had}}$	3ℓ selection, except: One medium τ_{had} candidate, of opposite charge to the total charge of the light leptons Two SS tight (T) leptons

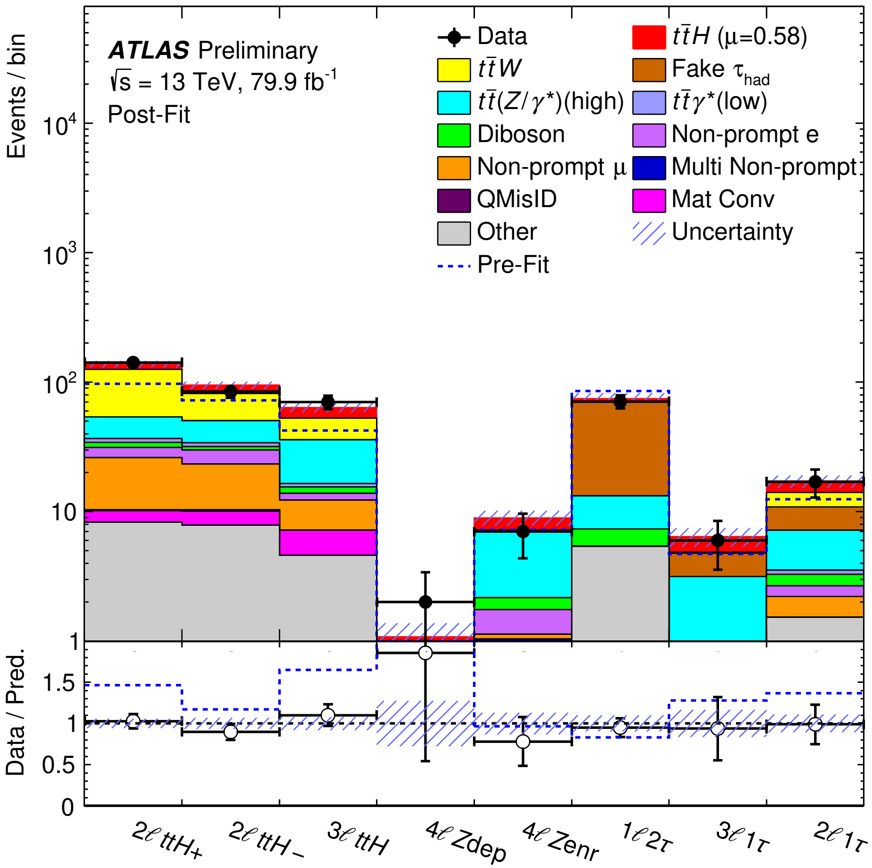
- **b-jet multiplicity + lepton charge asymmetry**

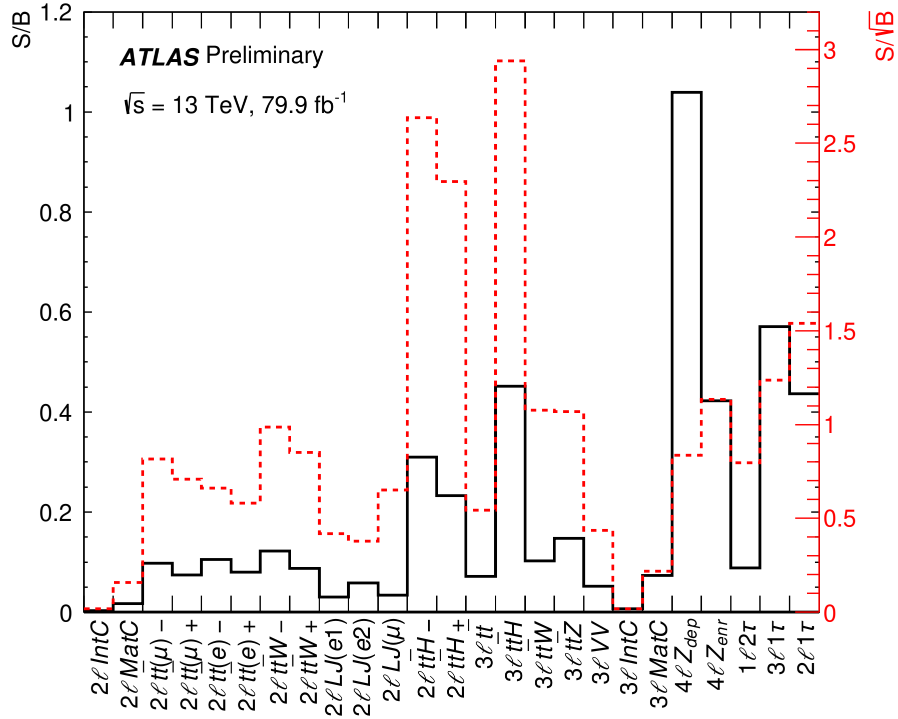


ttH multilepton

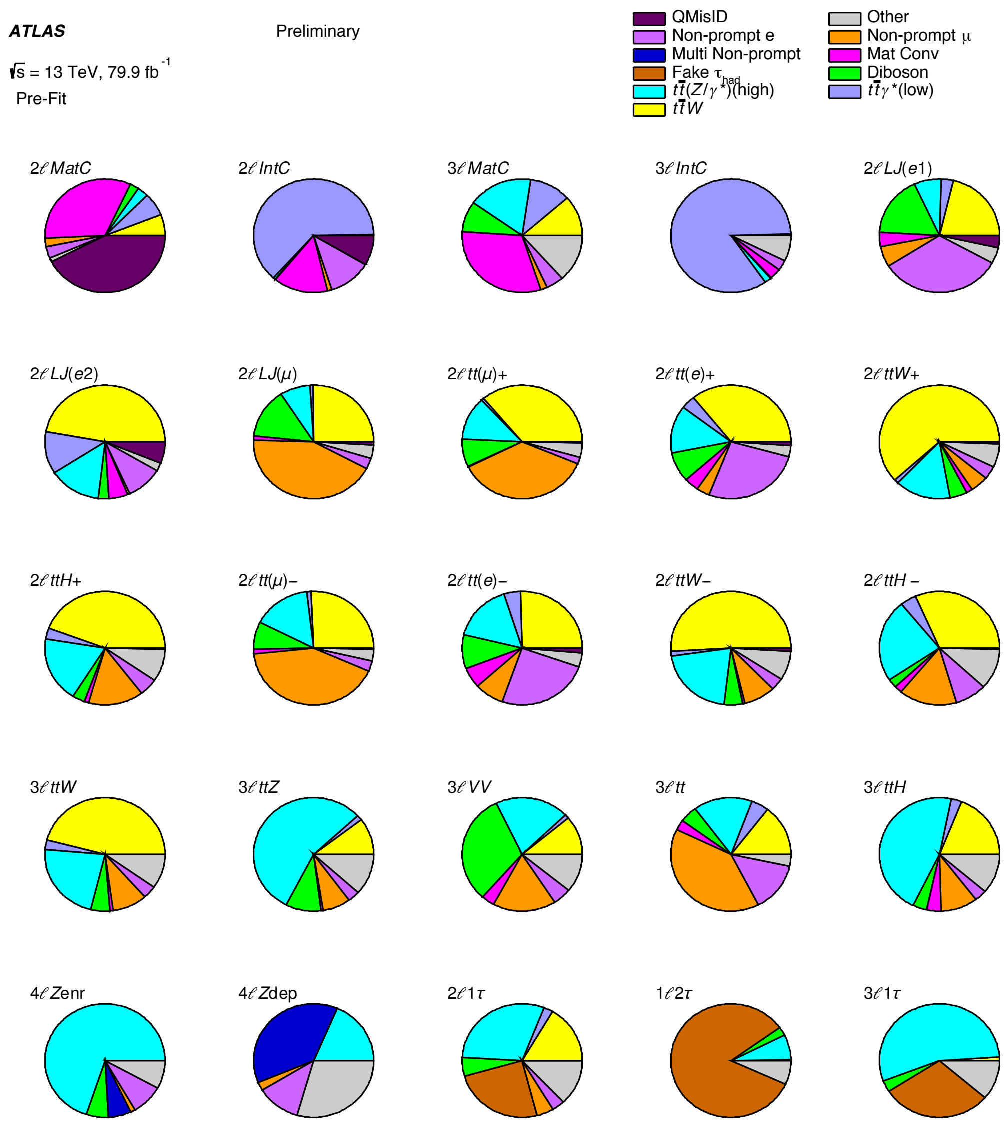
ATLAS-CONF-2019-045

- **Signal regions**

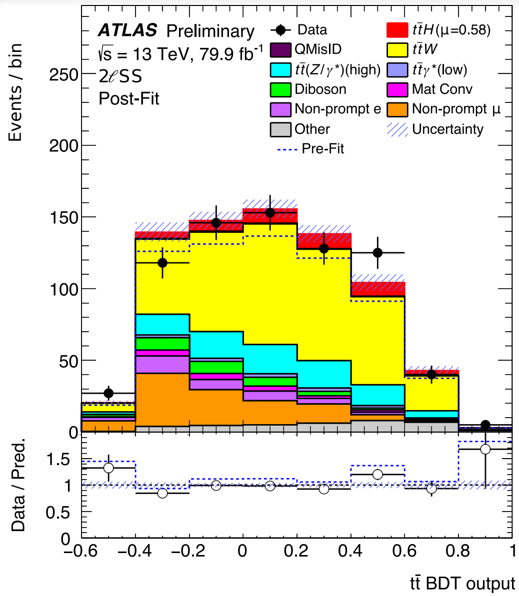


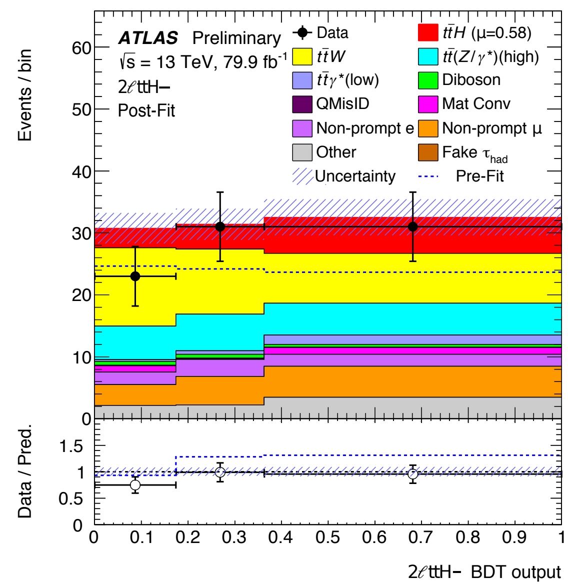


ATLAS-CONF-2019-045

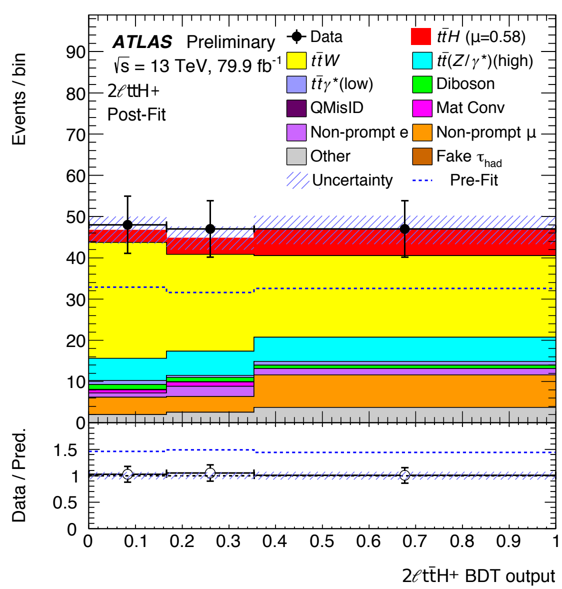


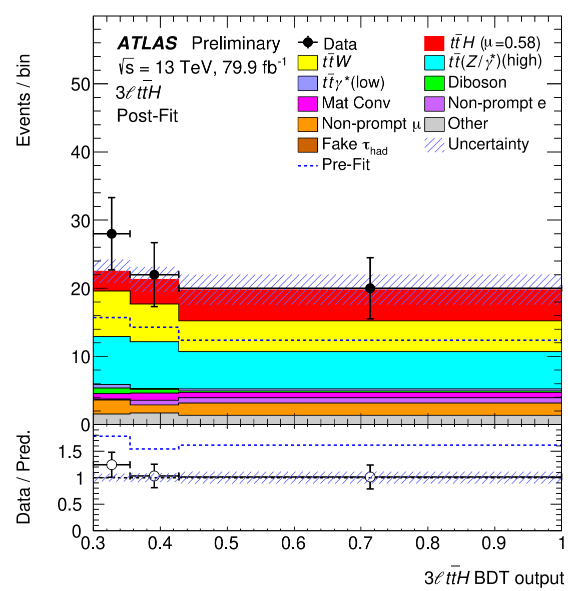
ttH multilepton





- **BDT outputs**

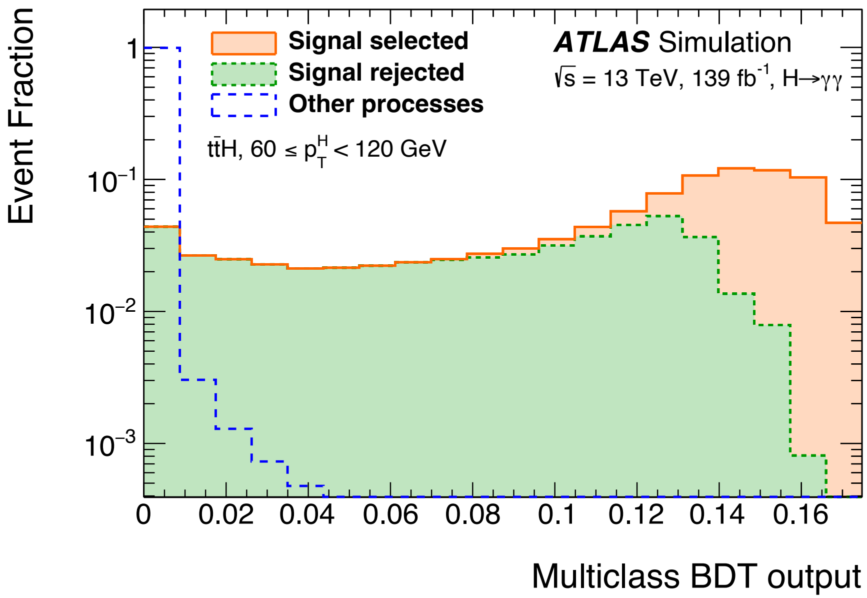




- **Systematics**

Uncertainty source	$\Delta\hat{\mu}$	
Jet energy scale and resolution	+0.13	−0.13
$t\bar{t}(Z/\gamma^*)$ (high mass) modelling	+0.09	−0.09
$t\bar{t}W$ modelling (radiation, generator, PDF)	+0.08	−0.08
Fake τ_{had} background estimate	+0.07	−0.07
$t\bar{t}W$ modelling (extrapolation)	+0.05	−0.05
$t\bar{t}H$ cross section	+0.05	−0.05
Simulation sample size	+0.05	−0.05
$t\bar{t}H$ modelling	+0.04	−0.04
Other background modelling	+0.04	−0.04
Jet flavour tagging and τ_{had} identification	+0.04	−0.04
Other experimental uncertainties	+0.03	−0.03
Luminosity	+0.03	−0.03
Diboson modelling	+0.01	−0.01
$t\bar{t}\gamma^*$ (low mass) modelling	+0.01	−0.01
Charge misassignment	+0.01	−0.01
Template fit (non-prompt leptons)	+0.01	−0.01
Total systematic uncertainty	+0.25	−0.22
Intrinsic statistical uncertainty	+0.23	−0.22
$t\bar{t}W$ normalisation factors	+0.10	−0.10
Non-prompt leptons normalisation factors (HF, material conversions)	+0.05	−0.05
Total statistical uncertainty	+0.26	−0.25
Total uncertainty	+0.36	−0.33

- **ttH STXS BDT multi-classifier**



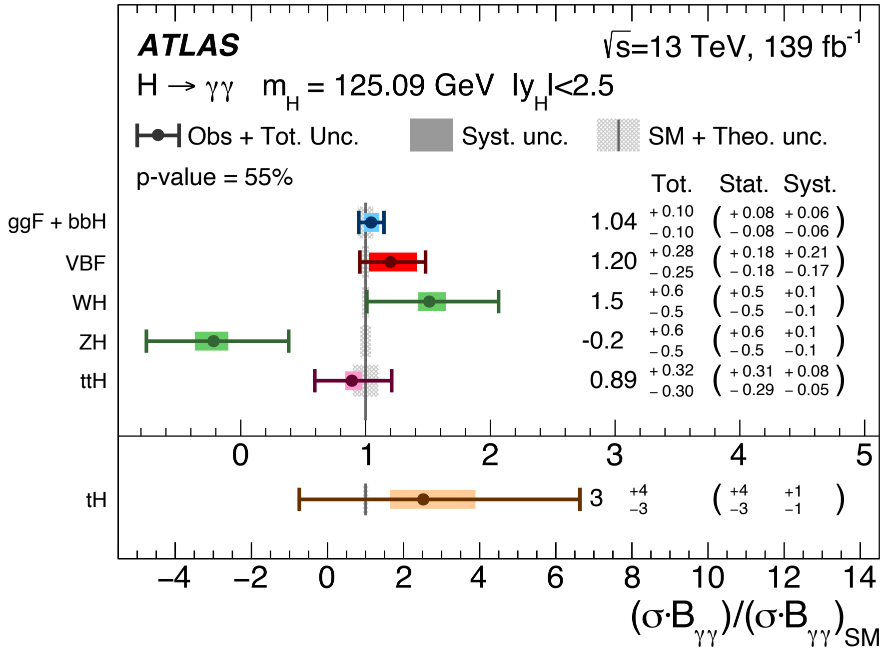
η_{γ_1}, η_{γ_2}, $p_{\mathrm{T}}^{\gamma\gamma}$, $y_{\gamma\gamma}$,
$p^{\dagger}_{\mathrm{T},jj}$, m_{jj}, and Δy, $\Delta\phi$, $\Delta\eta$ between j_1 and j_2,
$p_{\mathrm{T},\gamma\gamma j_1}$, $m_{\gamma\gamma j_1}$, $p_{\mathrm{T},\gamma\gamma jj}\dagger$, $m_{\gamma\gamma jj}$
Δy, $\Delta\phi$ between the $\gamma\gamma$ and jj systems,
minimum ΔR between jets and photons,
invariant mass of the system comprising all jets in the event,
dilepton p_{T}, di-e or di-μ invariant mass (leptons are required to be oppositely charged),
$E_{\mathrm{T}}^{\mathrm{miss}}$, p_{T} and transverse mass of the lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$ system,
p_{T}, η, ϕ of top-quark candidates, $m_{t_1 t_2}$
Number of jets†, of central jets ($|\eta| < 2.5$)†, of b-jets† and of leptons,
p_{T} of the highest-p_{T} jet, scalar sum of the p_{T} of all jets,
scalar sum of the transverse energies of all particles ($\sum E_{\mathrm{T}}$), $E_{\mathrm{T}}^{\mathrm{miss}}$ significance,
$\left|E_{\mathrm{T}}^{\mathrm{miss}} - E_{\mathrm{T}}^{\mathrm{miss}}(\text{primary vertex with the highest } \sum p^2_{\mathrm{T,track}})\right| > 30\,\mathrm{GeV}$
Top reconstruction BDT of the top-quark candidates,
$\Delta R(W, b)$ of t_2,
η_{j_F}, $m_{\gamma\gamma j_F}$
Average number of interactions per bunch crossing.

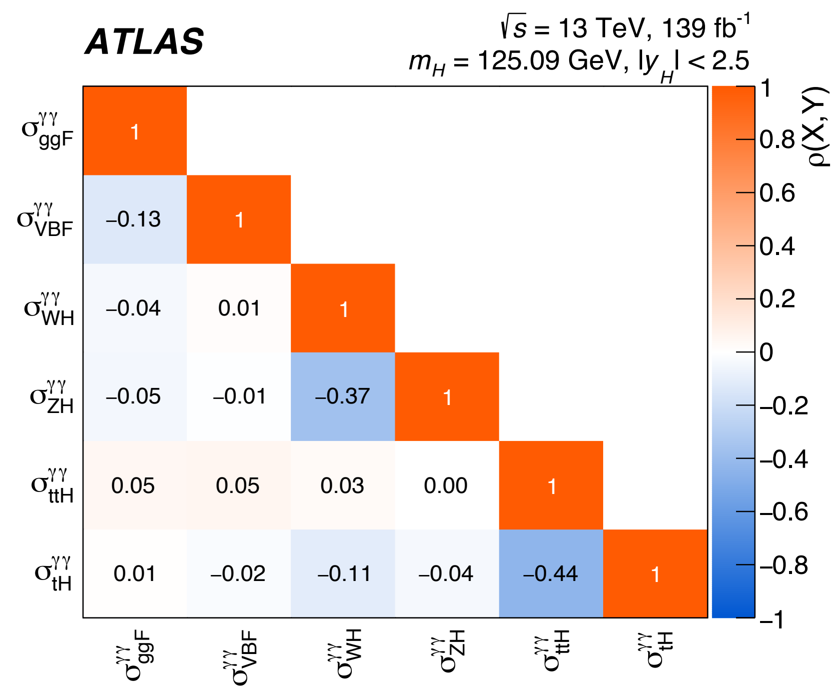
- **Signal vs background binary classifier**

STXS classes	Variables
Individual STXS classes from $gg \to H$, $qq' \to Hqq'$, $qq \to H\ell\nu$, $pp \to H\ell\ell$, $pp \to H\nu\bar{\nu}$	All multiclass BDT variables, $\boldsymbol{p}_{\mathrm{T}}^{\gamma\gamma}$ projected to the thrust axis of the $\gamma\gamma$ system ($p_{\mathrm{Tt}}^{\gamma\gamma}$), $\Delta\eta_{\gamma\gamma}$, $\eta^{\mathrm{Zepp}} = \frac{\eta_{\gamma\gamma}-\eta_{jj}}{2}$, $\phi^{*}_{\gamma\gamma} = \tan\left(\frac{\pi-\lvert\Delta\phi_{\gamma\gamma}\rvert}{2}\right)\sqrt{1-\tanh^{2}\left(\frac{\Delta\eta_{\gamma\gamma}}{2}\right)}$, $\cos\theta^{*}_{\gamma\gamma} = \left\lvert\frac{(E^{\gamma_1}+p_z^{\gamma_1})\cdot(E^{\gamma_2}-p_z^{\gamma_2})-(E^{\gamma_1}-p_z^{\gamma_1})\cdot(E^{\gamma_2}+p_z^{\gamma_2})}{m_{\gamma\gamma}+\sqrt{m^2_{\gamma\gamma}+(p_{\mathrm{T}}^{\gamma\gamma})^2}}\right\rvert$ Number of electrons and muons.
all $t\bar{t}H$ and tHW STXS classes combined	p_{T}, η, ϕ of γ_1 and γ_2, p_{T}, η, ϕ and b-tagging scores of the six highest-p_{T} jets, $E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$ significance, $E_{\mathrm{T}}^{\mathrm{miss}}$ azimuthal angle, Top reconstruction BDT scores of the top-quark candidates, p_{T}, η, ϕ of the two highest-p_{T} leptons.
$tHqb$	$p_{\mathrm{T}}^{\gamma\gamma}/m_{\gamma\gamma}$, $\eta_{\gamma\gamma}$, p_{T}, invariant mass, BDT score and $\Delta R(W,b)$ of t_1, p_{T}, η of t_2, p_{T}, η of j_F, Angular variables: $\Delta\eta_{\gamma\gamma t_1}$, $\Delta\theta_{\gamma\gamma t_2}$, $\Delta\theta_{t_1 j_F}$, $\Delta\theta_{t_2 j_F}$, $\Delta\theta_{\gamma\gamma j_F}$ Invariant mass variables: $m_{\gamma\gamma j_F}$, $m_{t_1 j_F}$, $m_{t_2 j_F}$, $m_{\gamma\gamma t_1}$ Number of jets with $p_{\mathrm{T}} > 25$ GeV, Number of b-jets with $p_{\mathrm{T}} > 25$ GeV*; Number of leptons*, $E_{\mathrm{T}}^{\mathrm{miss}}$ significance*

ttH + tH H→γγ

HIGG-2020-16
JHEP 07 (2023) 088

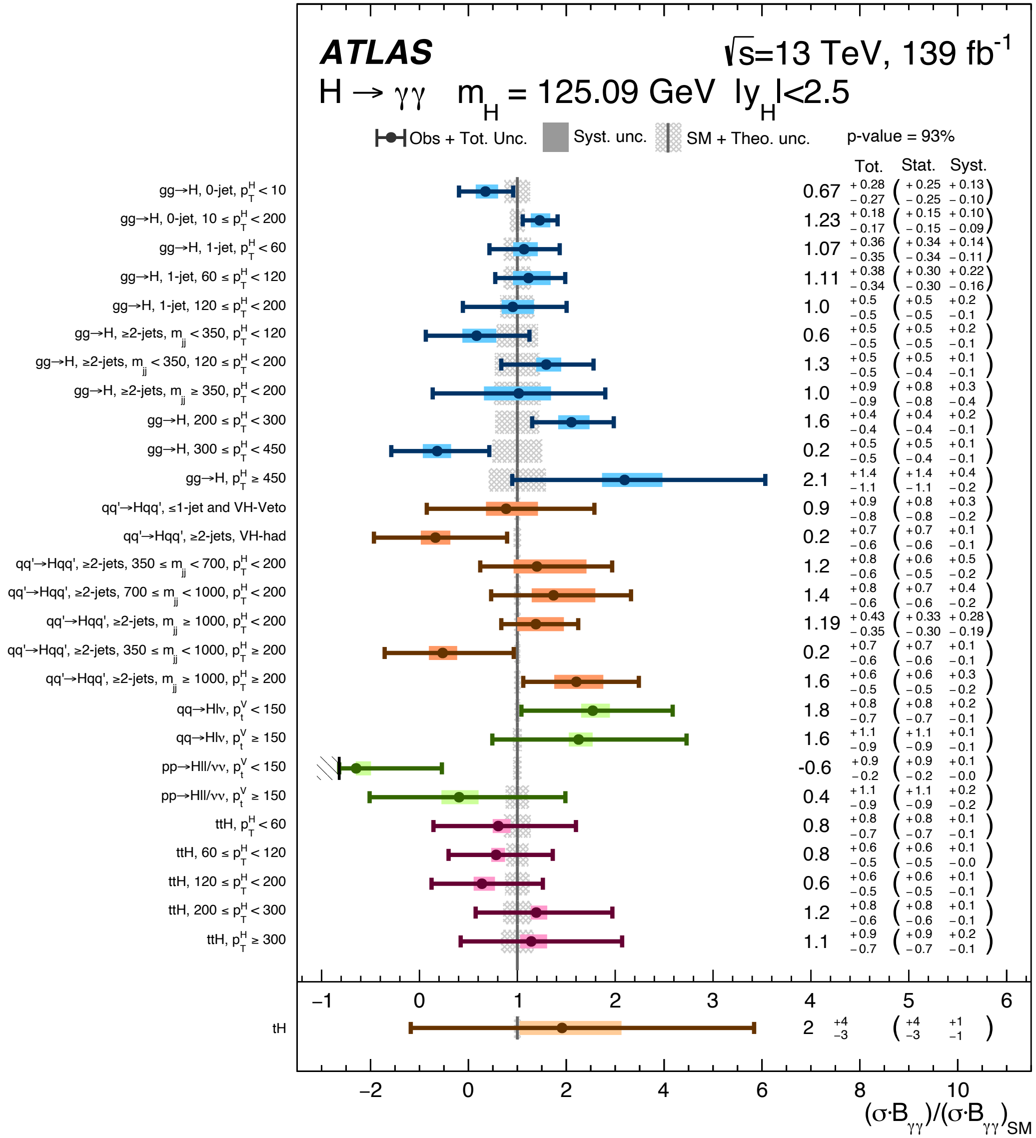




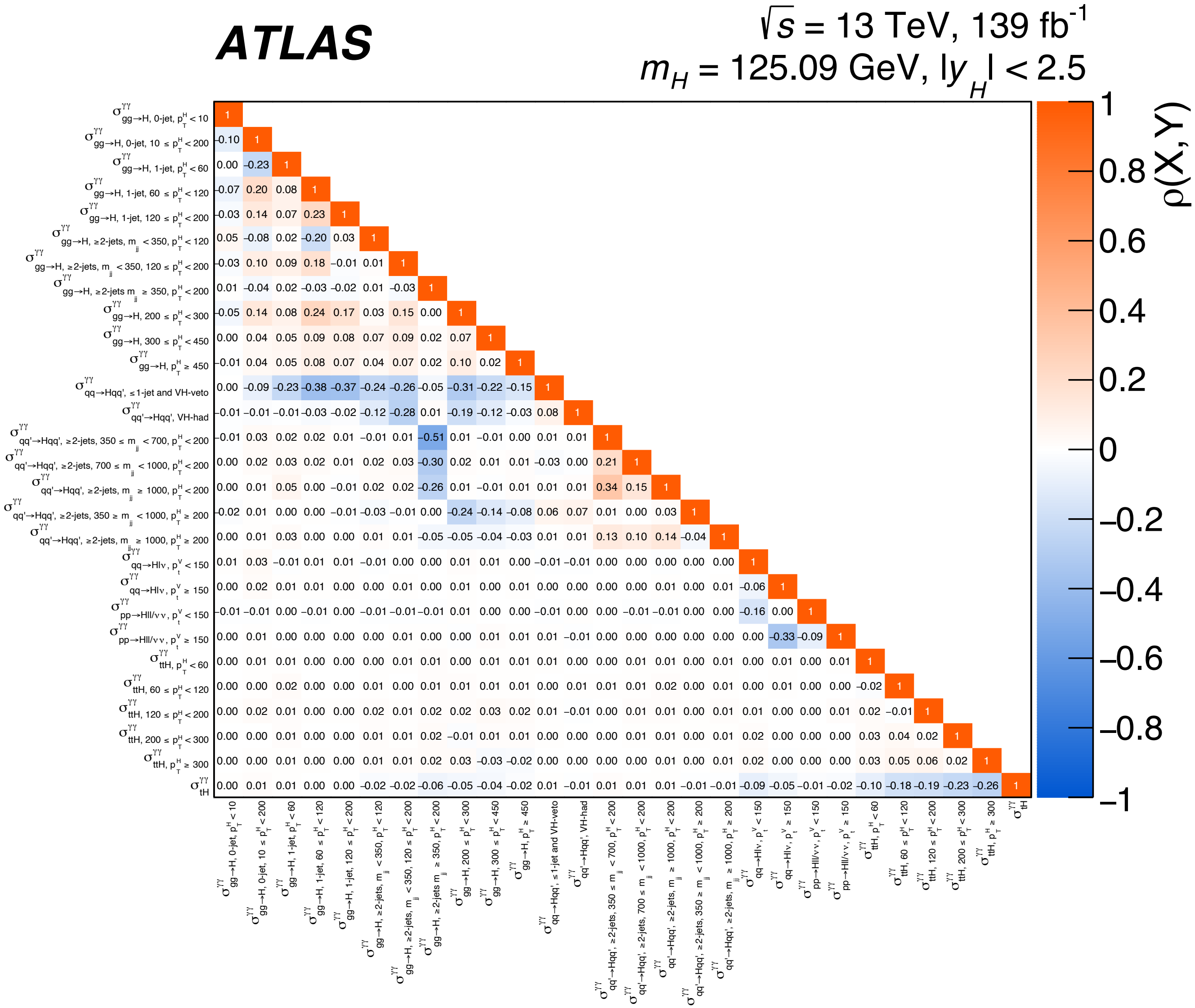
	$\sigma^{\gamma\gamma}_{ggF}$	$\sigma^{\gamma\gamma}_{VBF}$	$\sigma^{\gamma\gamma}_{WH}$	$\sigma^{\gamma\gamma}_{ZH}$	$\sigma^{\gamma\gamma}_{ttH}$	$\sigma^{\gamma\gamma}_{tH}$
$\sigma^{\gamma\gamma}_{ggF}$	1					
$\sigma^{\gamma\gamma}_{VBF}$	−0.13	1				
$\sigma^{\gamma\gamma}_{WH}$	−0.04	0.01	1			
$\sigma^{\gamma\gamma}_{ZH}$	−0.05	−0.01	−0.37	1		
$\sigma^{\gamma\gamma}_{ttH}$	0.05	0.05	0.03	0.00	1	
$\sigma^{\gamma\gamma}_{tH}$	0.01	−0.02	−0.11	−0.04	−0.44	1

ttH + tH H→γγ

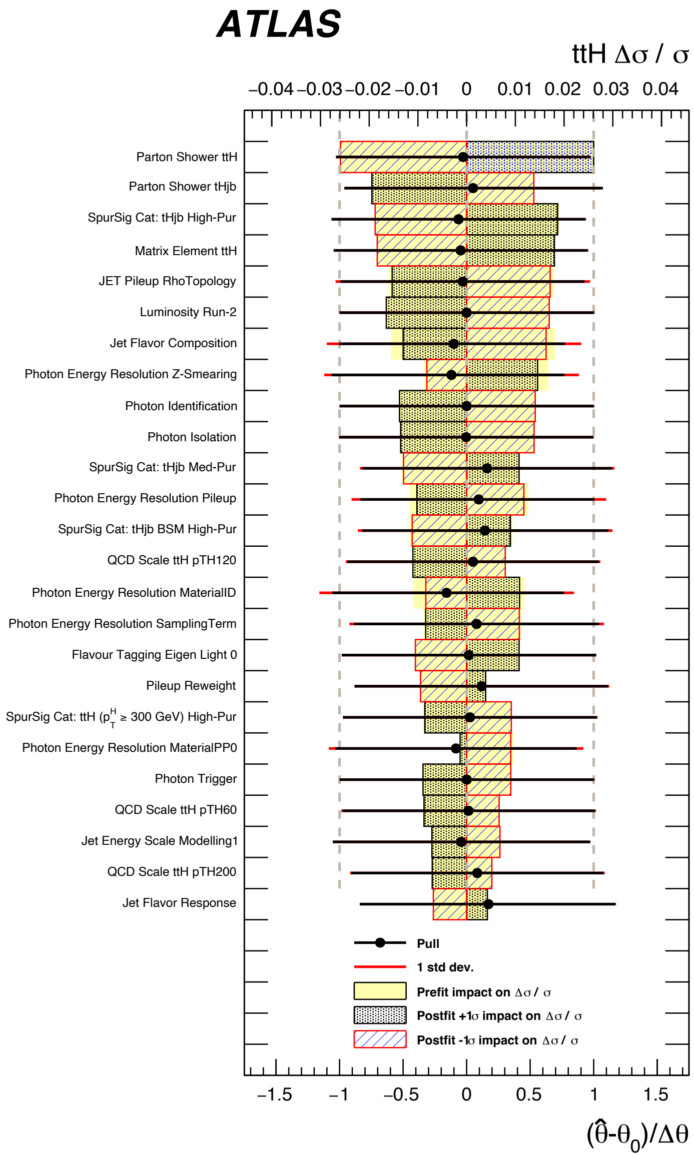
HIGG-2020-16
JHEP 07 (2023) 088

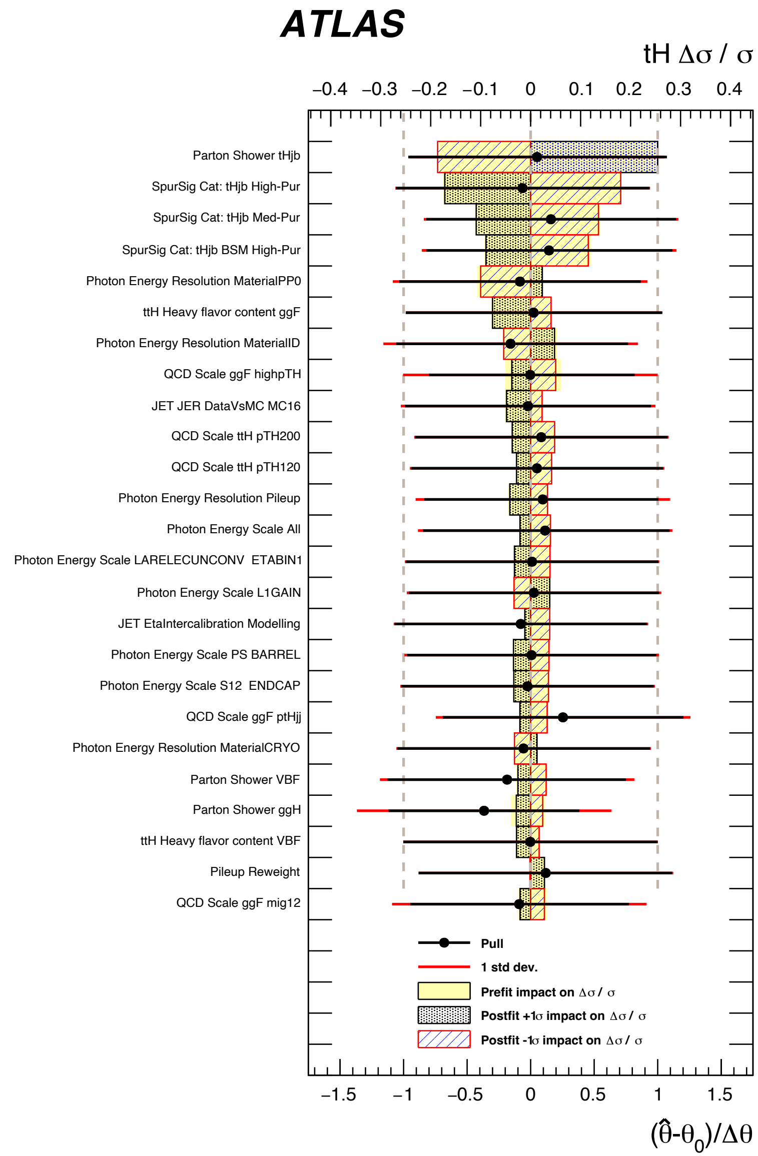


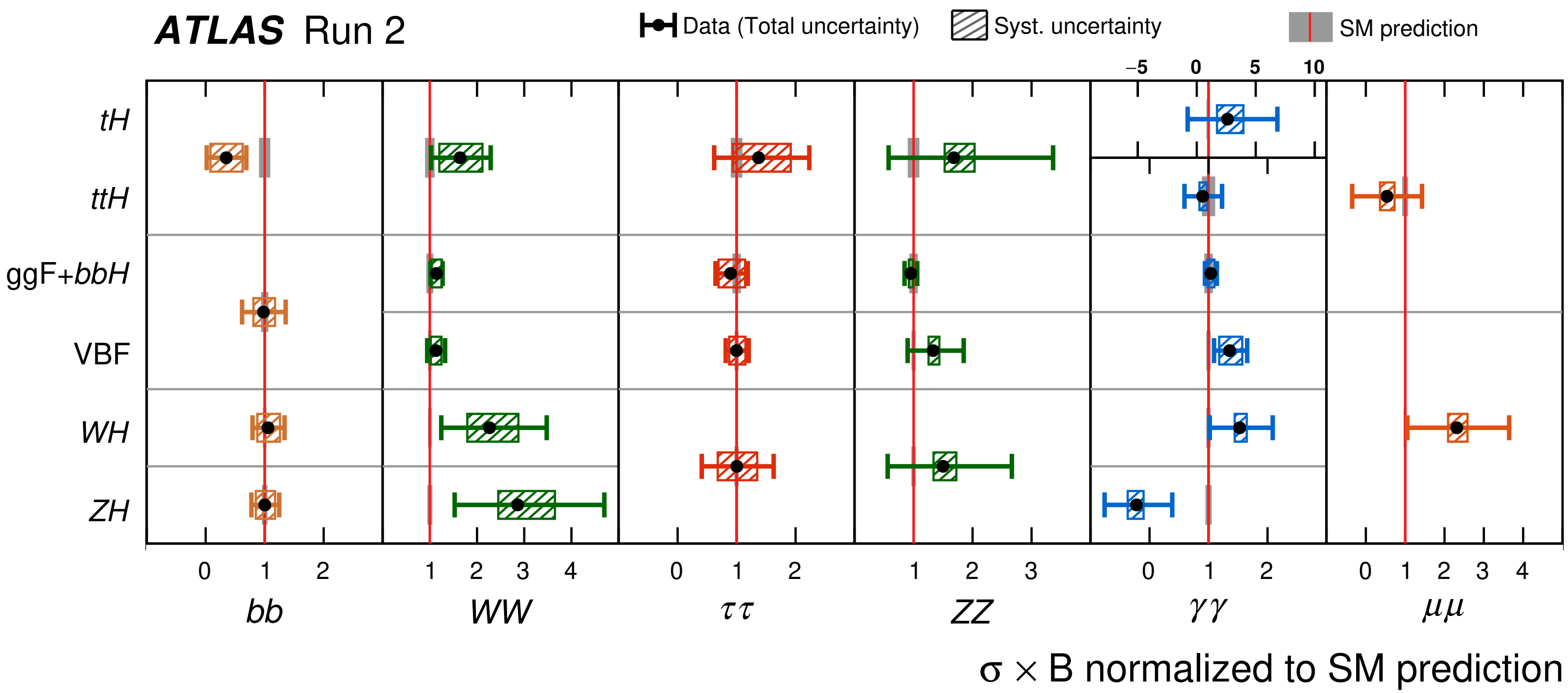
ttH + tH H→γγ


ATLAS
√s = 13 TeV, 139 fb-1
mH = 125.09 GeV, |yH| < 2.5
ρ(X,Y)
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1

ttH + tH H→γγ

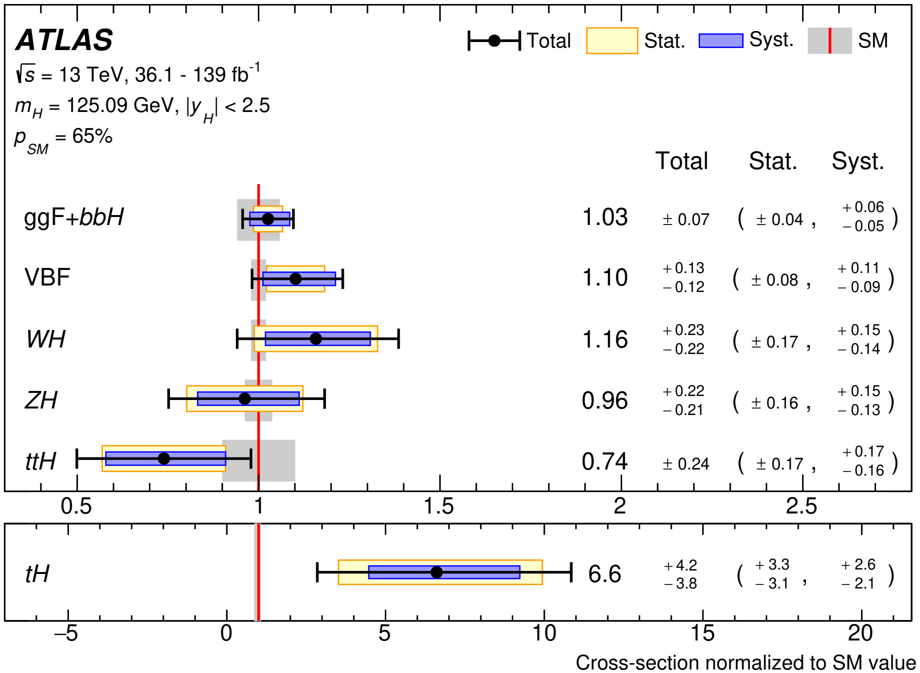

ATLAS
ttH Δσ / σ
−0.04 −0.03 −0.02 −0.01 0 0.01 0.02 0.03 0.04
Parton Shower ttH
Parton Shower tHjb
SpurSig Cat: tHjb High-Pur
Matrix Element ttH
JET Pileup RhoTopology
Luminosity Run-2
Jet Flavor Composition
Photon Energy Resolution Z-Smearing
Photon Identification
Photon Isolation
SpurSig Cat: tHjb Med-Pur
Photon Energy Resolution Pileup
SpurSig Cat: tHjb BSM High-Pur
QCD Scale ttH pTH120
Photon Energy Resolution MaterialID
Photon Energy Resolution SamplingTerm
Flavour Tagging Eigen Light 0
Pileup Reweight
SpurSig Cat: ttH (p_T^H ≥ 300 GeV) High-Pur
Photon Energy Resolution MaterialPP0
Photon Trigger
QCD Scale ttH pTH60
Jet Energy Scale Modelling1
QCD Scale ttH pTH200
Jet Flavor Response
Pull
1 std dev.
Prefit impact on Δσ / σ
Postfit +1σ impact on Δσ / σ
Postfit -1σ impact on Δσ / σ
−1.5 −1 −0.5 0 0.5 1 1.5
$(\hat{\theta}-\theta_0)/\Delta\theta$

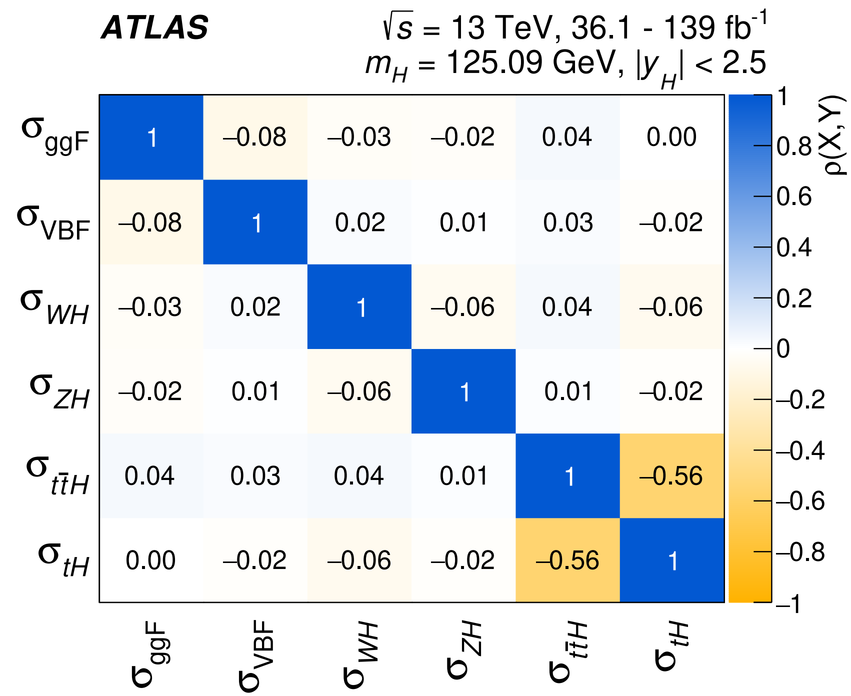

ATLAS
tH Δσ / σ
−0.4 −0.3 −0.2 −0.1 0 0.1 0.2 0.3 0.4
Parton Shower tHjb
SpurSig Cat: tHjb High-Pur
SpurSig Cat: tHjb Med-Pur
SpurSig Cat: tHjb BSM High-Pur
Photon Energy Resolution MaterialPP0
ttH Heavy flavor content ggF
Photon Energy Resolution MaterialID
QCD Scale ggF highpTH
JET JER DataVsMC MC16
QCD Scale ttH pTH200
QCD Scale ttH pTH120
Photon Energy Resolution Pileup
Photon Energy Scale All
Photon Energy Scale LARELECUNCONV ETABIN1
Photon Energy Scale L1GAIN
JET EtaIntercalibration Modelling
Photon Energy Scale PS BARREL
Photon Energy Scale S12 ENDCAP
QCD Scale ggF ptHjj
Photon Energy Resolution MaterialCRYO
Parton Shower VBF
Parton Shower ggH
ttH Heavy flavor content VBF
Pileup Reweight
QCD Scale ggF mig12
Pull
1 std dev.
Prefit impact on Δσ / σ
Postfit +1σ impact on Δσ / σ
Postfit -1σ impact on Δσ / σ
−1.5 −1 −0.5 0 0.5 1 1.5
$(\hat{\theta}-\theta_0)/\Delta\theta$



ATLAS Run 2
Data (Total uncertainty)
Syst. uncertainty
SM prediction
tH
ttH
ggF+bbH
VBF
WH
ZH
−5
0
5
10
0 1 2
1 2 3 4
0 1 2
1 2 3
0 1 2
0 1 2 3 4
bb
WW
ττ
ZZ
γγ
μμ
σ × B normalized to SM prediction

Higgs combination

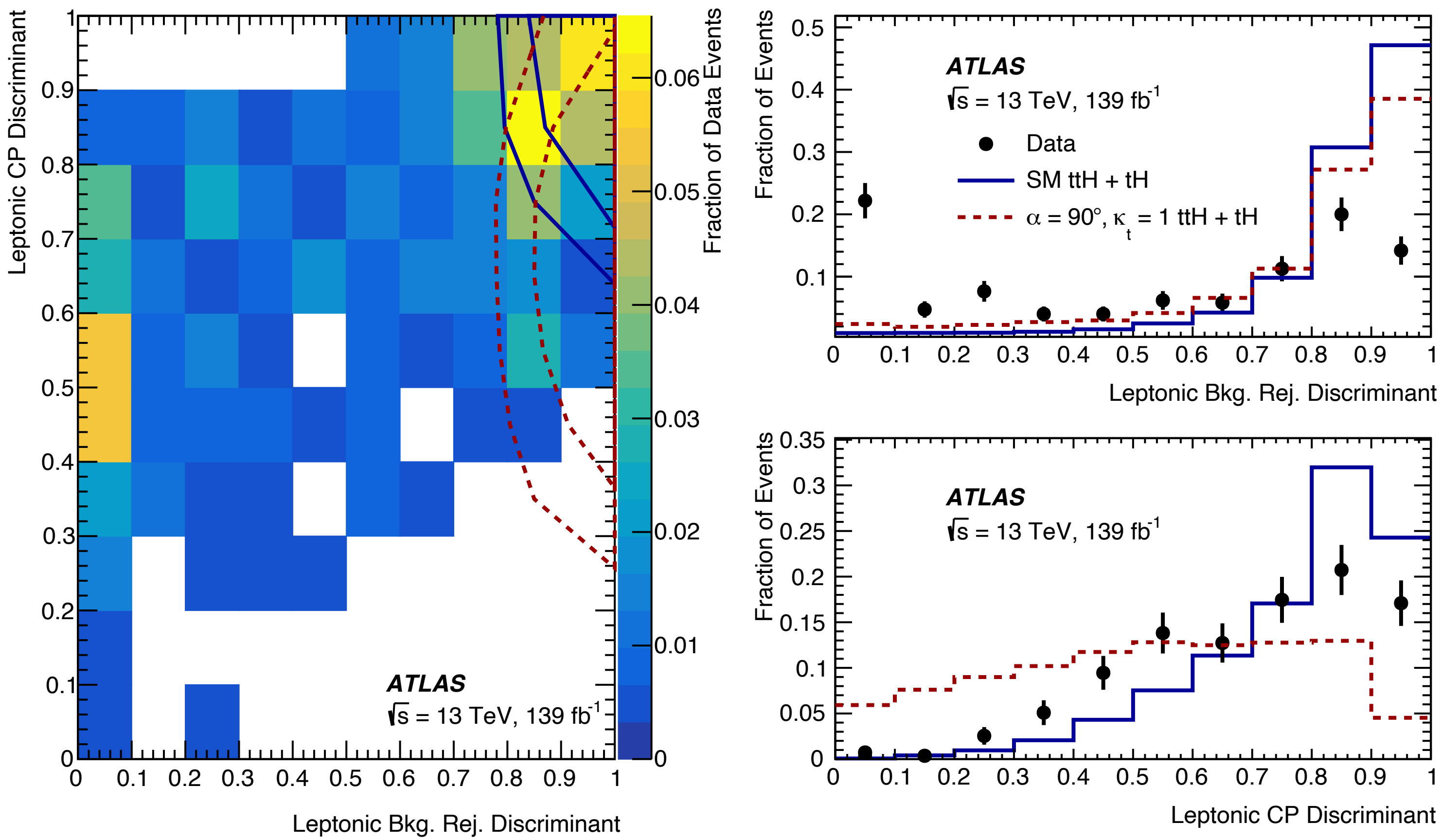


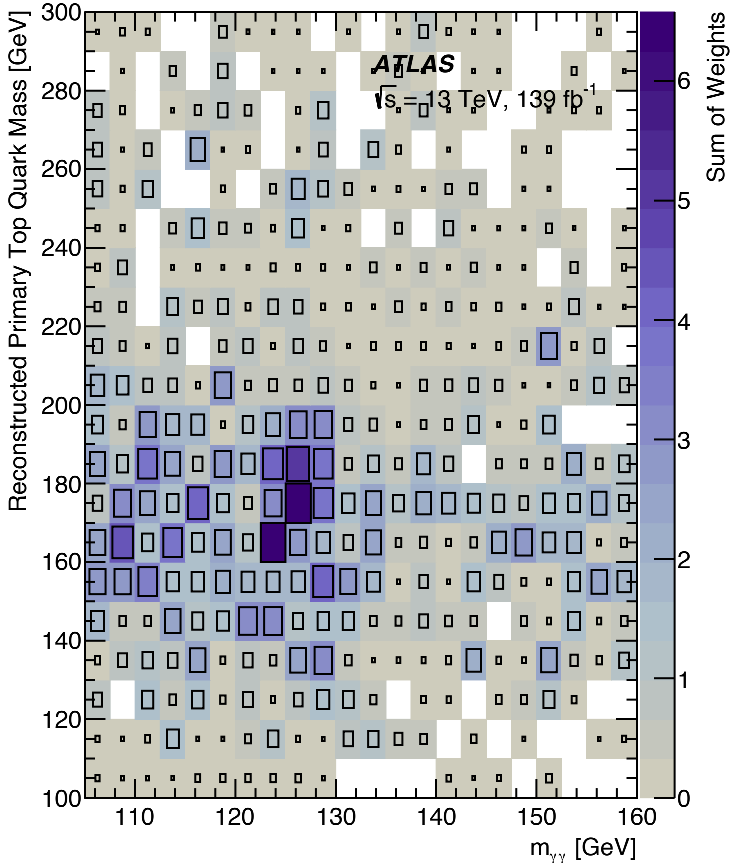


	σggF	σVBF	σWH	σZH	σttH	σtH
σggF	1	−0.08	−0.03	−0.02	0.04	0.00
σVBF	−0.08	1	0.02	0.01	0.03	−0.02
σWH	−0.03	0.02	1	−0.06	0.04	−0.06
σZH	−0.02	0.01	−0.06	1	0.01	−0.02
σttH	0.04	0.03	0.04	0.01	1	−0.56
σtH	0.00	−0.02	−0.06	−0.02	−0.56	1

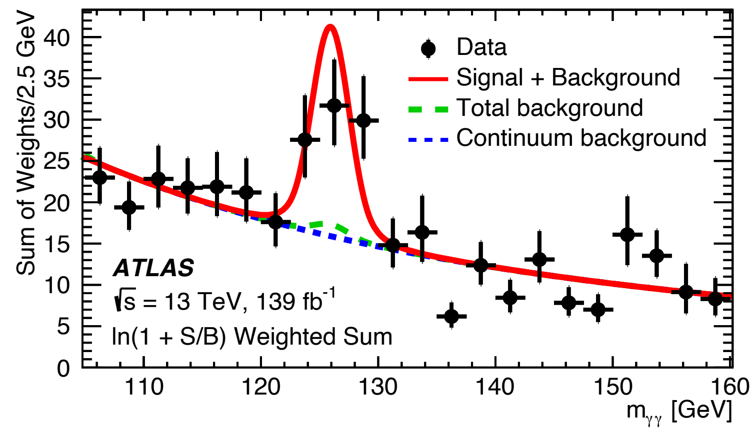
ttH + tH H→γγ CP

HIGG-2019-01 Phys. Rev. Lett. 125 (2020) 061802

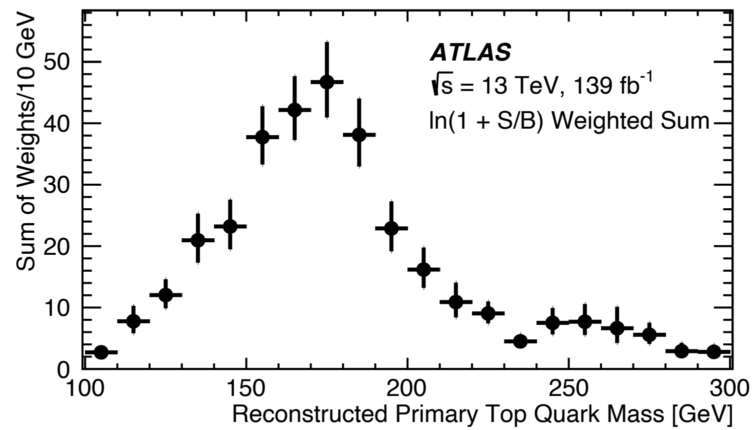




ATLAS
√s = 13 TeV, 139 fb-1
Reconstructed Primary Top Quark Mass [GeV]
mγγ [GeV]
Sum of Weights



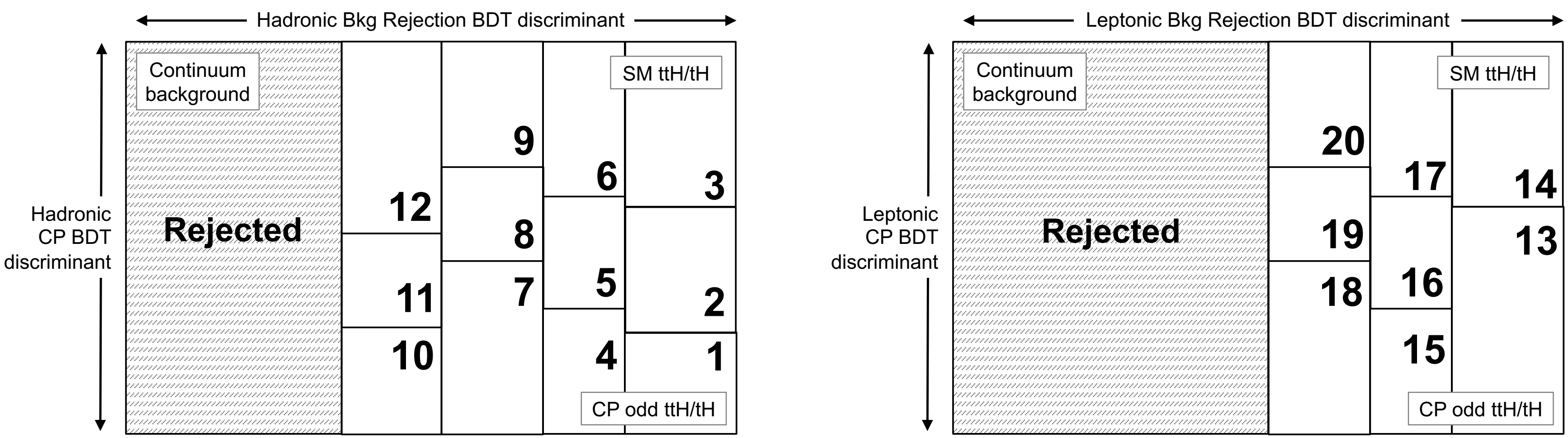
Data
Signal + Background
Total background
Continuum background
ATLAS
√s = 13 TeV, 139 fb-1
ln(1 + S/B) Weighted Sum
Sum of Weights/2.5 GeV
mγγ [GeV]



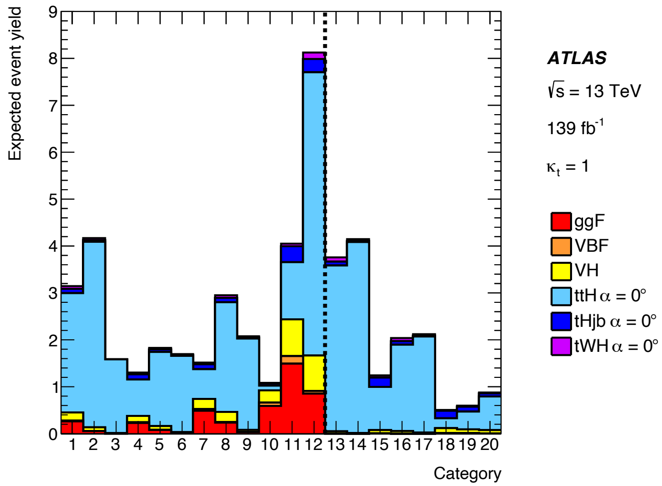
ATLAS
√s = 13 TeV, 139 fb-1
ln(1 + S/B) Weighted Sum
Sum of Weights/10 GeV
Reconstructed Primary Top Quark Mass [GeV]

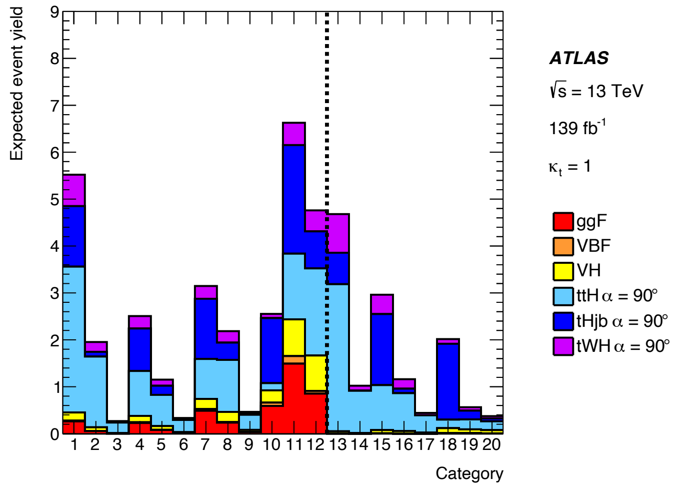
ttH + tH H→γγ CP

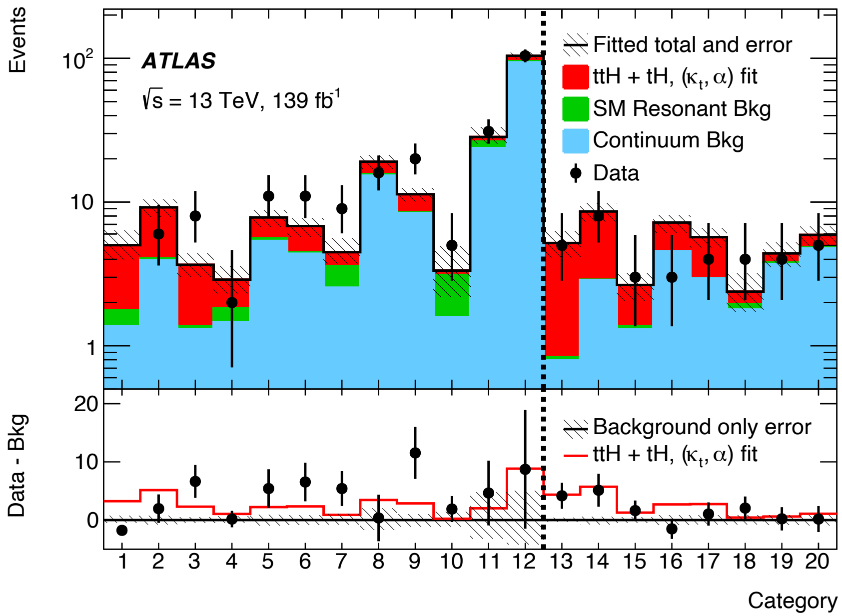
HIGG-2019-01 Phys. Rev. Lett. 125 (2020) 061802



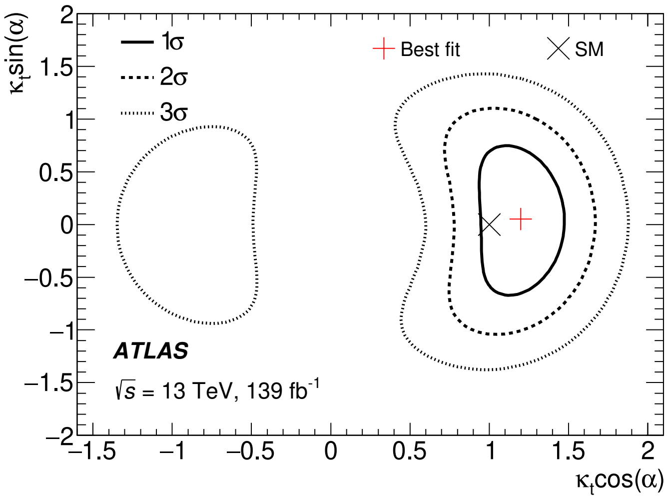
HIGG-2019-01 Phys. Rev. Lett. 125 (2020) 061802

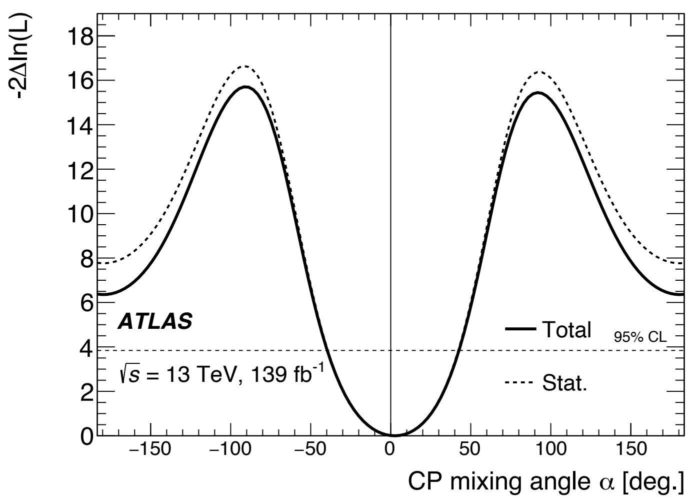




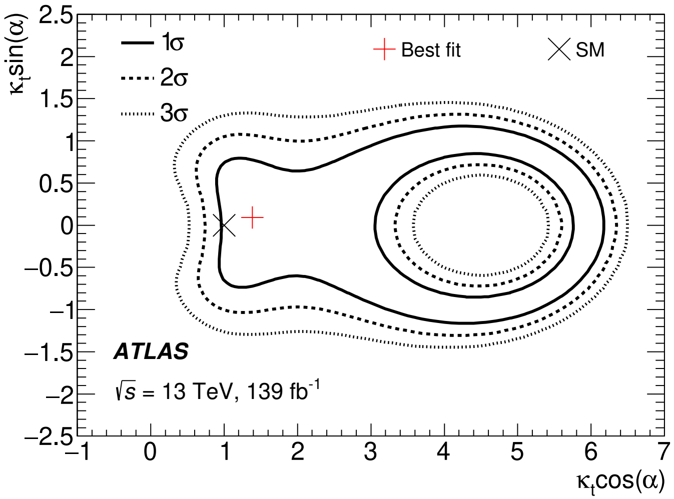


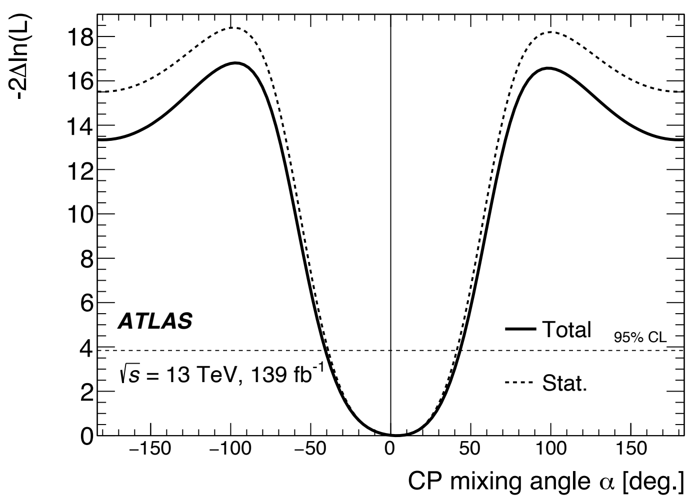
- **Gluon and photon effective Higgs couplings constrained with other H->γγ prod. modes**

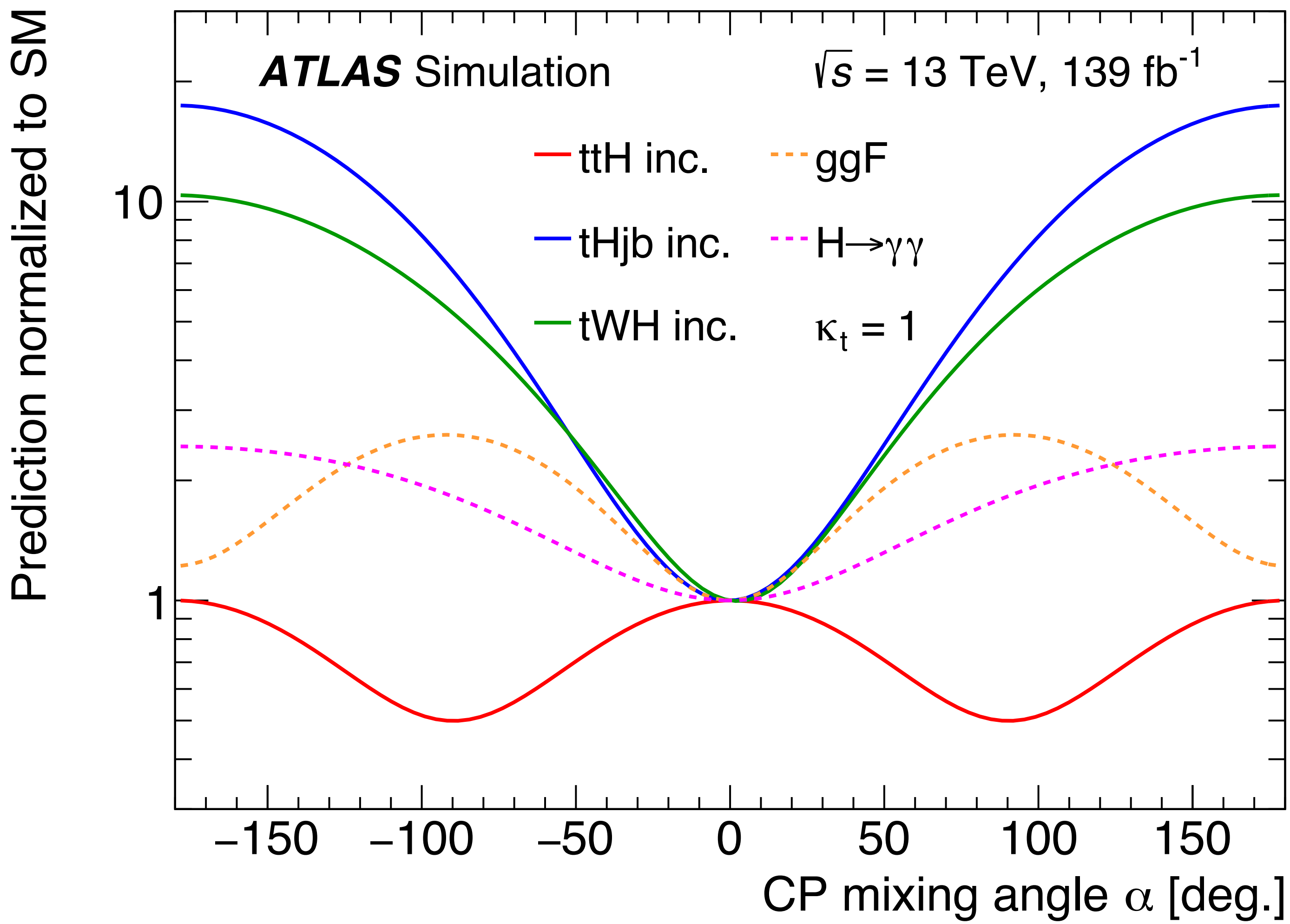




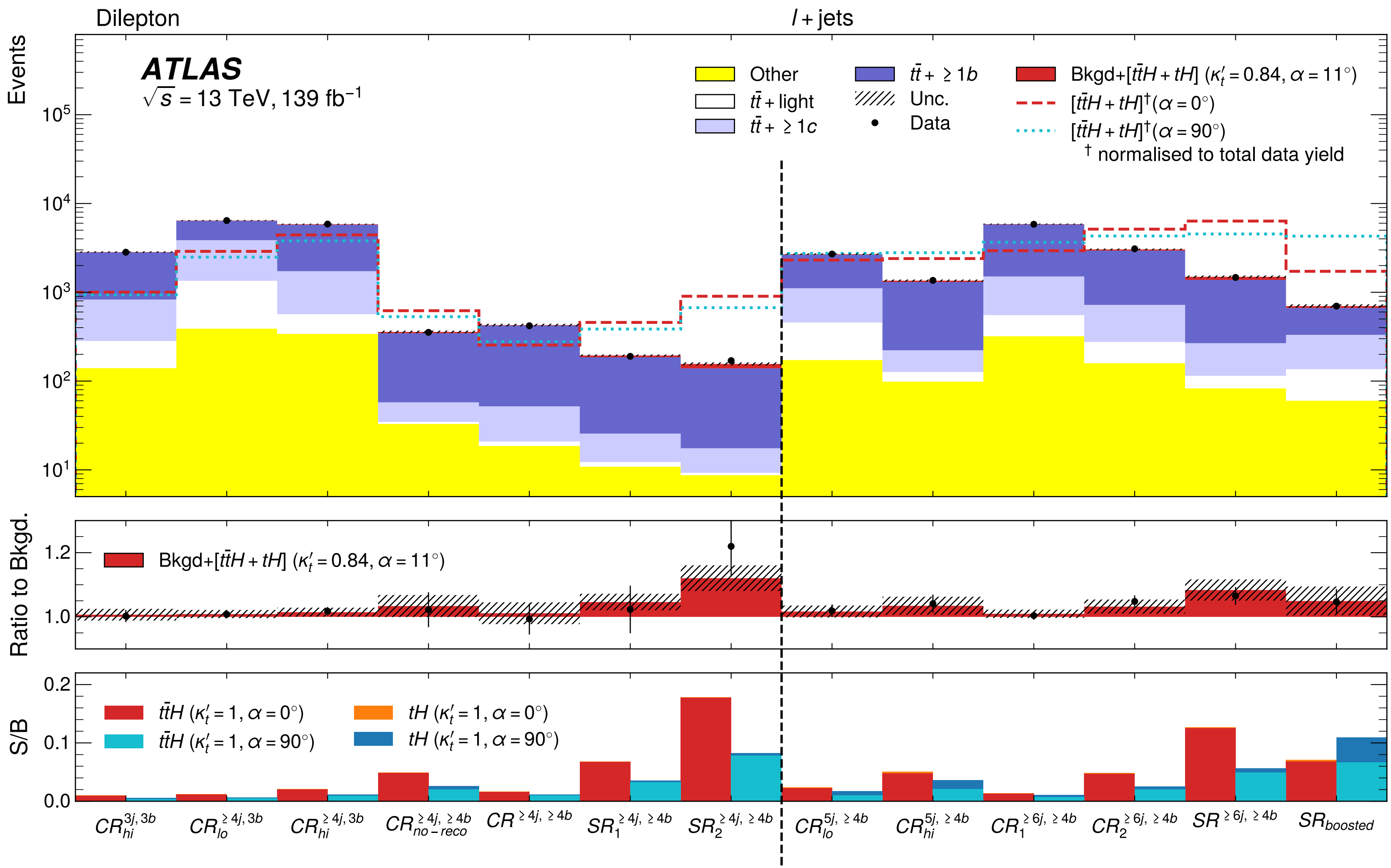
- **Gluon and photon effective Higgs couplings parametrised vs κ_t and α**






ATLAS Simulation
√s = 13 TeV, 139 fb-1
ttH inc.
tHjb inc.
tWH inc.
ggF
H→γγ
κt = 1
Prediction normalized to SM
10
1
−150
−100
−50
0
50
100
150
CP mixing angle α [deg.]

HIGG-2020-03, Subm. to PLB



ttH + tH H→bb CP

HIGG-2020-03, Subm. to PLB

Uncertainty source	$\Delta\alpha\,[^\circ]$	
Process modelling		
Signal modelling	+8.8	-14
$t\bar{t}+\geq 1b$ modelling		
$t\bar{t}+\geq 1b$ 4V5 FS	+23	-37
$t\bar{t}+\geq 1b$ NLO matching	+22	-33
$t\bar{t}+\geq 1b$ fractions	+14	-21
$t\bar{t}+\geq 1b$ FSR	+5.2	-9.9
$t\bar{t}+\geq 1b$ PS & hadronisation	+16	-24
$t\bar{t}+\geq 1b$ $p_{\mathrm{T}}^{b\bar{b}}$ shape	+5.4	-4.6
$t\bar{t}+\geq 1b$ ISR	+14	-24
$t\bar{t}+\geq 1c$ modelling	+6.6	-11
$t\bar{t}+$ light modelling	+2.5	-4.7
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+8.7	-15
c-mis-tag rates	+6.7	-11
l-mis-tag rates	+2.3	-2.7
Jet energy scale and resolution		
b-jet energy scale	+1.6	-3.8
Jet energy scale (flavour)	+7.8	-11
Jet energy scale (pileup)	+5.2	-7.9
Jet energy scale (remaining)	+8.1	-13
Jet energy resolution	+5.7	-9.3
Luminosity	$\leq \pm 1$	
Other sources	+4.9	-8
Total systematic uncertainty	+41	-54
$t\bar{t}+\geq 1b$ normalisation	+8.2	-13
κ_t'	+17	-33
Total statistical uncertainty	+32	-49
Total uncertainty	+52	-73

Uncertainty source	$\Delta\kappa_t'$	
Process modelling		
Signal modelling	+0.10	-0.10
$t\bar{t}+\geq 1b$ modelling		
$t\bar{t}+\geq 1b$ 4V5 FS	+0.08	-0.23
$t\bar{t}+\geq 1b$ NLO matching	+0.15	-0.30
$t\bar{t}+\geq 1b$ fractions	+0.09	-0.21
$t\bar{t}+\geq 1b$ FSR	+0.01	-0.02
$t\bar{t}+\geq 1b$ PS & hadronisation	+0.09	-0.20
$t\bar{t}+\geq 1b$ $p_{\mathrm{T}}^{b\bar{b}}$ shape	+0.07	-0.11
$t\bar{t}+\geq 1b$ ISR	+0.07	-0.17
$t\bar{t}+\geq 1c$ modelling	+0.04	-0.10
$t\bar{t}+$ light modelling	+0.00	-0.01
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+0.06	-0.12
c-mis-tag rates	+0.03	-0.07
l-mis-tag rates	+0.01	-0.03
Jet energy scale and resolution		
b-jet energy scale	+0.02	-0.02
Jet energy scale (flavour)	+0.01	-0.05
Jet energy scale (pileup)	+0.02	-0.05
Jet energy scale (remaining)	+0.04	-0.08
Jet energy resolution	+0.03	-0.09
Luminosity	$\leq \pm 0.01$	
Other sources	+0.03	-0.07
Total systematic uncertainty	+0.29	-0.45
$t\bar{t}+\geq 1b$ normalisation	+0.05	-0.15
α	+0.08	-0.07
Total statistical uncertainty	+0.09	-0.10
Total uncertainty	+0.30	-0.46