Search for the SM Higgs boson in the $t\bar{t}H$ production channel using the ATLAS detector

Kun Liu

(CPPM, CNRS/IN2P3, Aix-Marseille Université)

John Keller

(DESY)

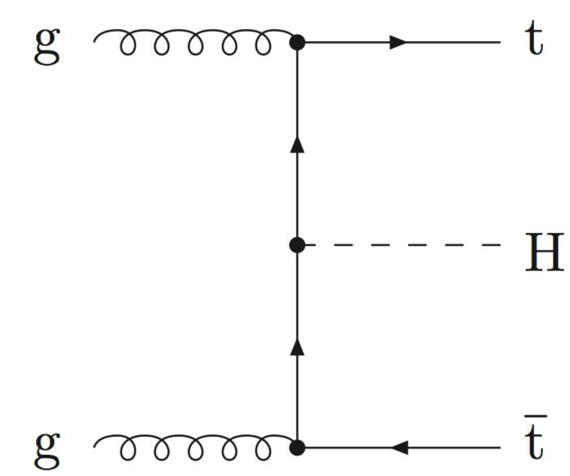
on behalf of the ATLAS collaboration

ICHEP @ Chicago

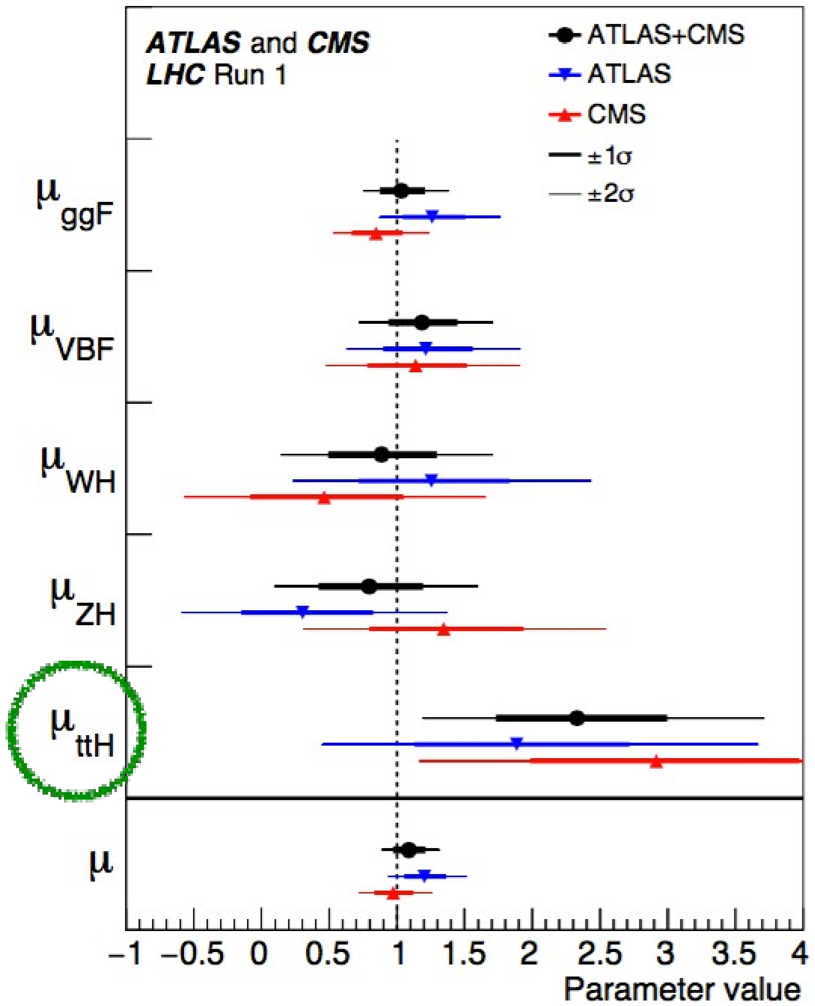
August 4, 2016

Motivation

- Direct measurement of Higgs-Top Yukawa coupling via $t\bar{t}H$ production → any deviation might be hint for new physics.
- $t\bar{t}H$ signal strength (μ_{ttH}) has been measured in LHC Run 1: 4.4 sigma combined significance, cross-section above SM value but consistent within large uncertainty.
- LHC Run 2 analysis benefits from large increase of the $t\bar{t}H$ cross section, though backgrounds increase at a comparable rate in the signal regions.



Cross section (fb) @NLO	$t\bar{t}H$	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}$ (NNLO)
8 TeV	133	232	206	2,53E+05
13 TeV	507	566	760	8,32E+05
13 TeV / 8TeV	3.8	2.4	3.7	3.3



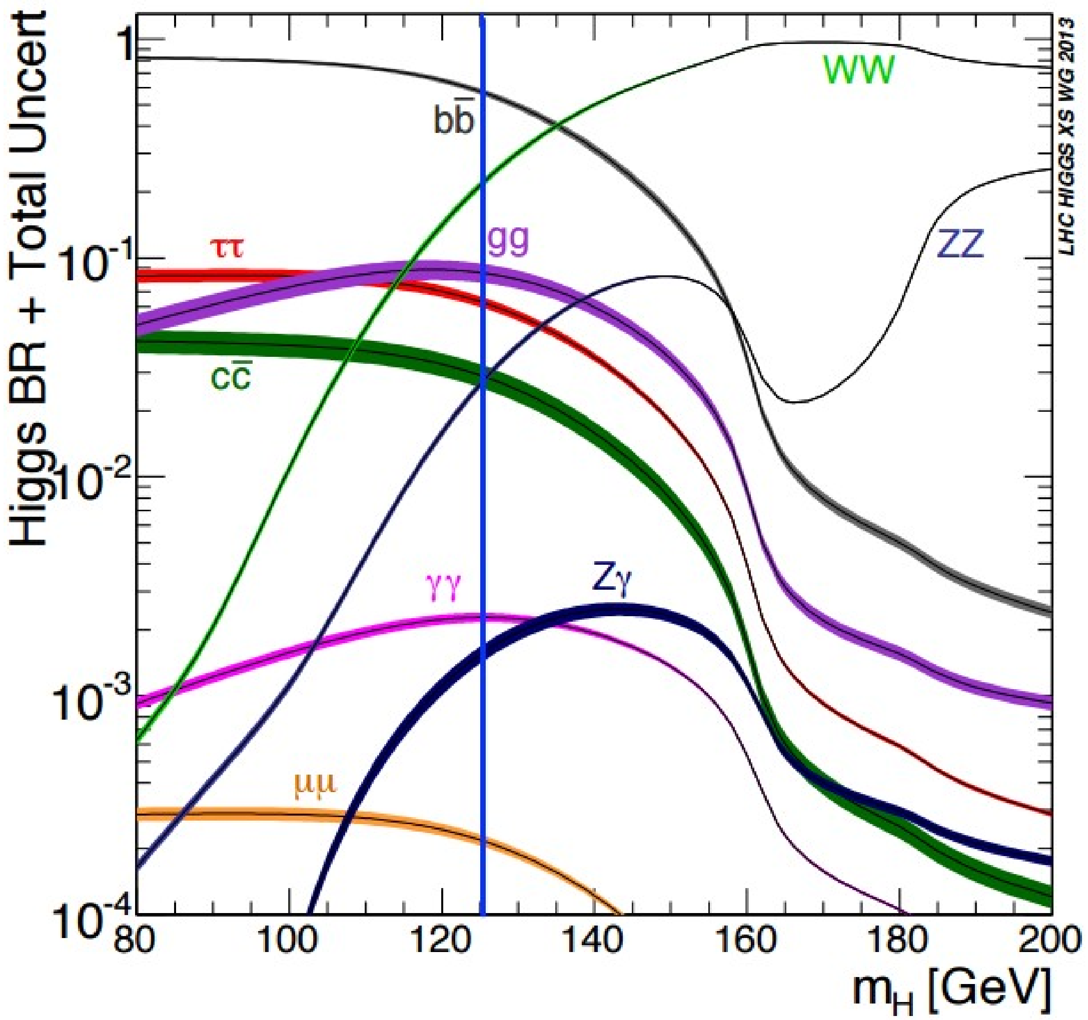
- This presentation: First ATLAS Run 2 $t\bar{t}H$ results, with total luminosity of 13.2 or 13.3 fb^{-1}.

ATLAS Run-2 search for the $t\bar{t}H$ process

- $t\bar{t}H$ cross section at 13 TeV is 507 fb → 1% of total Higgs production cross section.

- Search for the $t\bar{t}H$ production in many Higgs decay modes (branching ratio ~ 89%).

Higgs decay mode	Branching ratio [%]
H→ bb	58.1
H→ WW	21.5
H→ ττ	6.3
H→ ZZ	2.6
H→ γγ	0.23



Search for the $t\bar{t}H$ ($H \to bb$) process

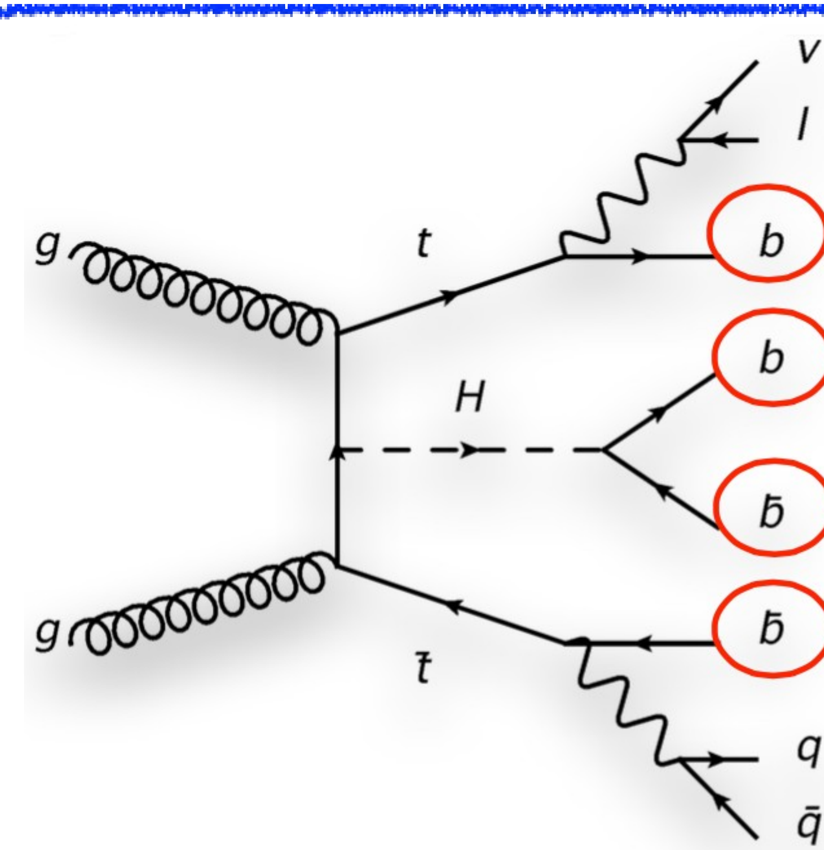
ATLAS-CONF-2016-080

- $t\bar{t}H$ cross section at 13 TeV is 507 fb → 1% of total Higgs production cross section.
- Search for the $t\bar{t}H$ production in many Higgs decay modes (branching ratio ~ 89%).

Higgs decay mode	Branching ratio [%]
H→ bb	58.1
H→ WW	21.5
H→ ττ	6.3
H→ ZZ	2.6
H→ γγ	0.23

$t\bar{t}H$(bb) channel has largest branching ratio but large background, and offers sensitivity to the Higgs-Bottom Yukawa coupling.

$t\bar{t}H$(bb) Feynman diagram



$t\bar{t}$ semi-leptonic decay

$t\bar{t}H(bb)$ analysis: event selection and background

- Event selection (event triggered by single lepton triggers)

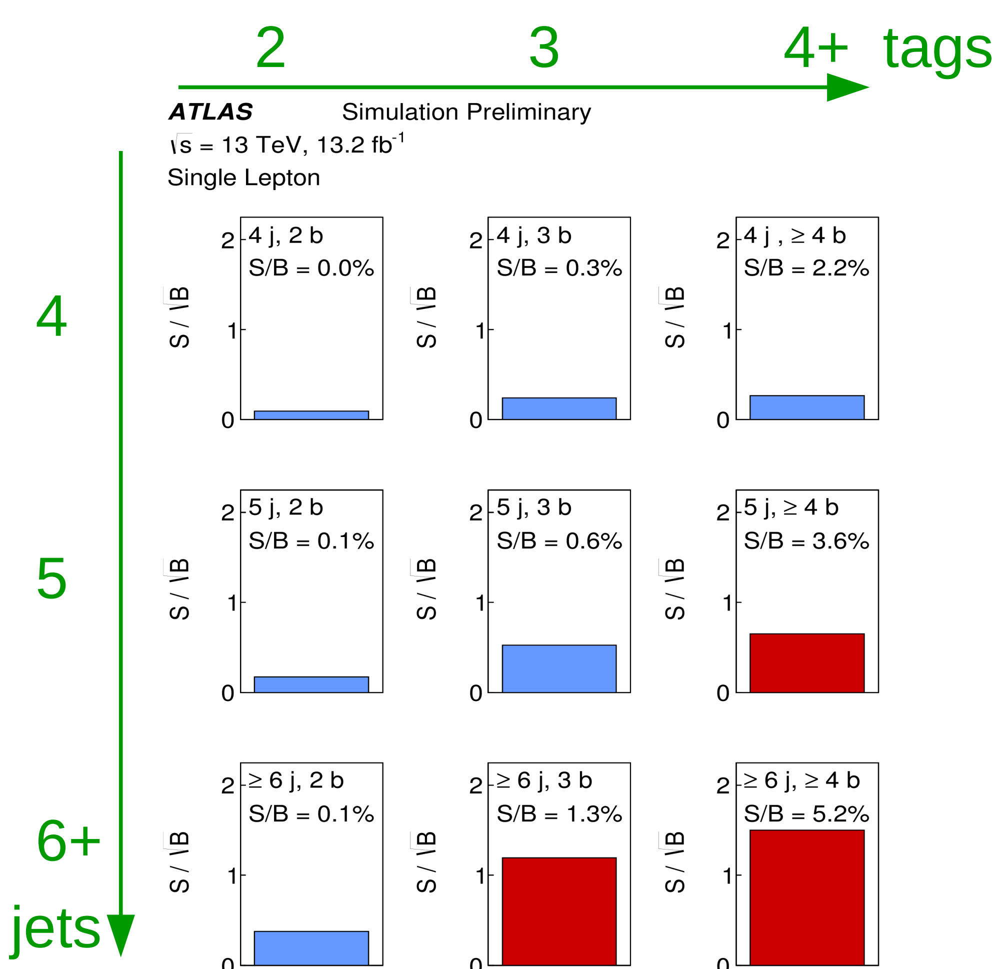
Single lepton channel
(one leptonic W decay)

- one electron or muon
- at least 4 jets
- at least 2 b-tagged jets

Dilepton channel
(two leptonic W decays)

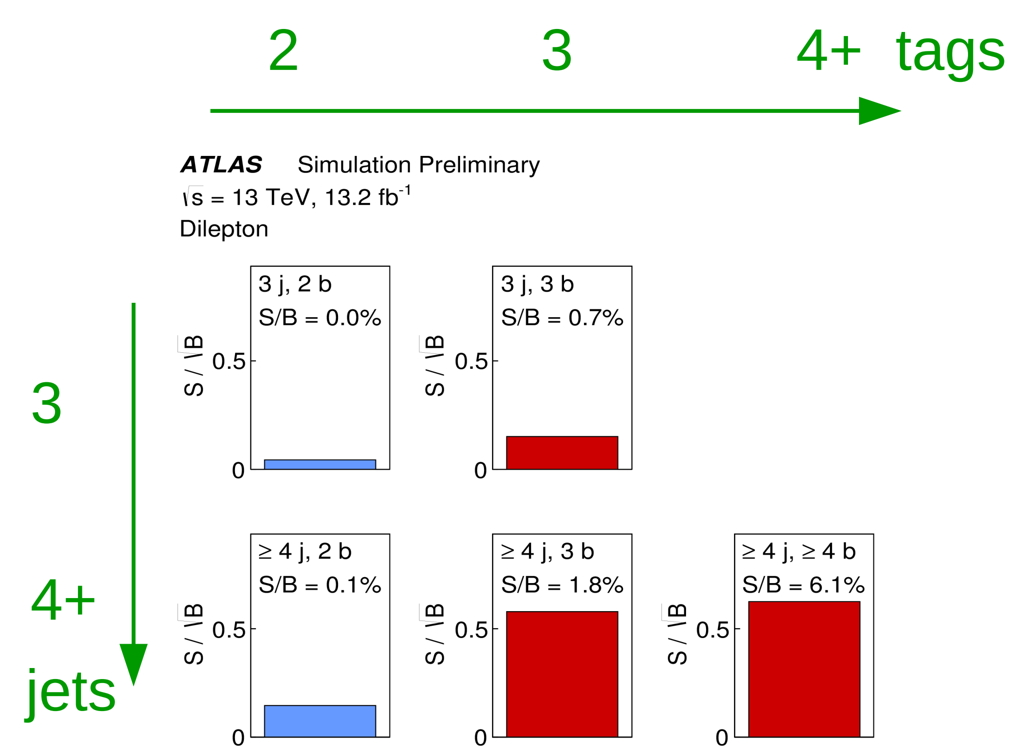
- 2 opposite charge light (e,μ) leptons
- at least 3 jets
- at least 2 b-tagged jets

- Events are categorised according to no. of jets and no. of b-tagged jets.



control regions

signal regions



$t\bar{t}H(bb)$ analysis: event selection and background

- Event selection (event triggered by single lepton triggers)

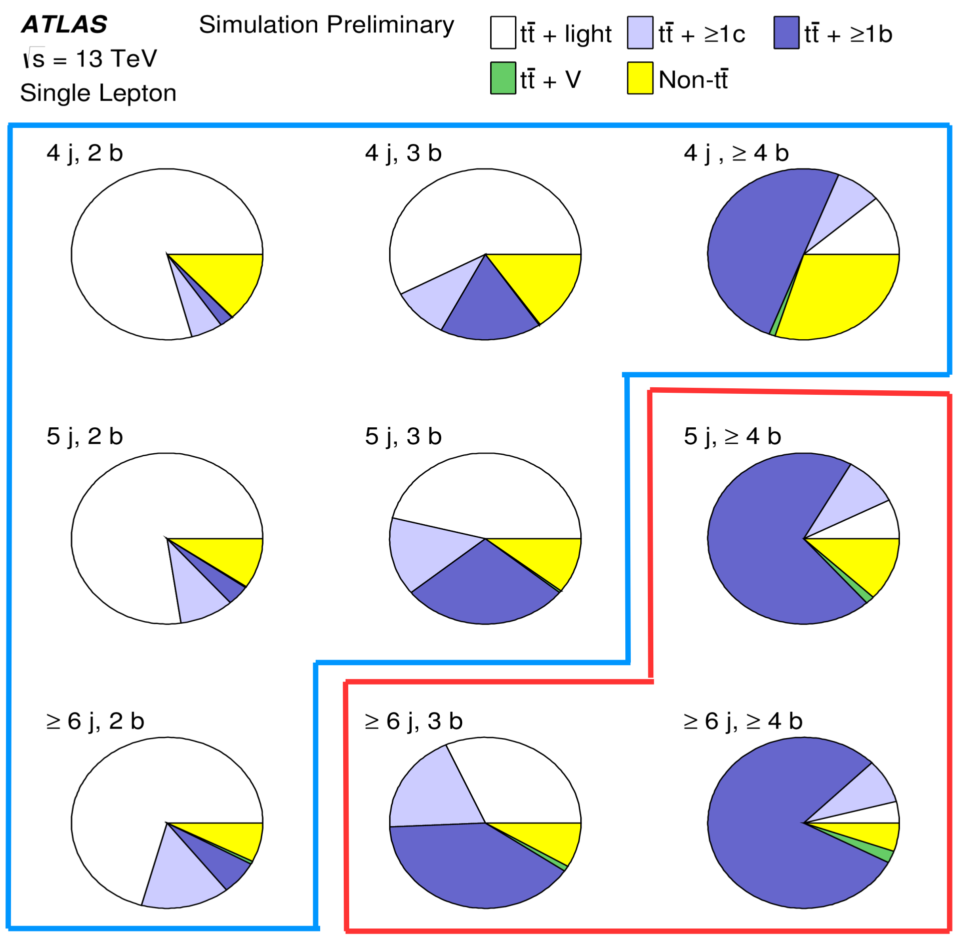
Single lepton channel
(one leptonic W decay)

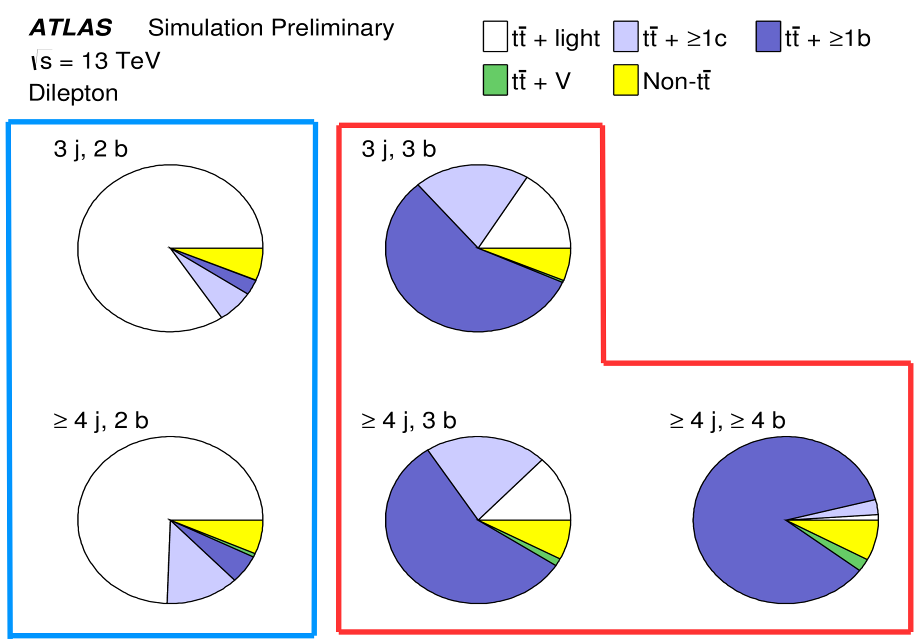
- one electron or muon
- at least 4 jets
- at least 2 b-tagged jets

Dilepton channel
(two leptonic W decays)

- 2 opposite charge light (e,μ) leptons
- at least 3 jets
- at least 2 b-tagged jets

- $t\bar{t}$ + ≥1 b-jet, $t\bar{t}$ + ≥1 c-jet, and $t\bar{t}$ + light-jets are the dominant backgrounds.

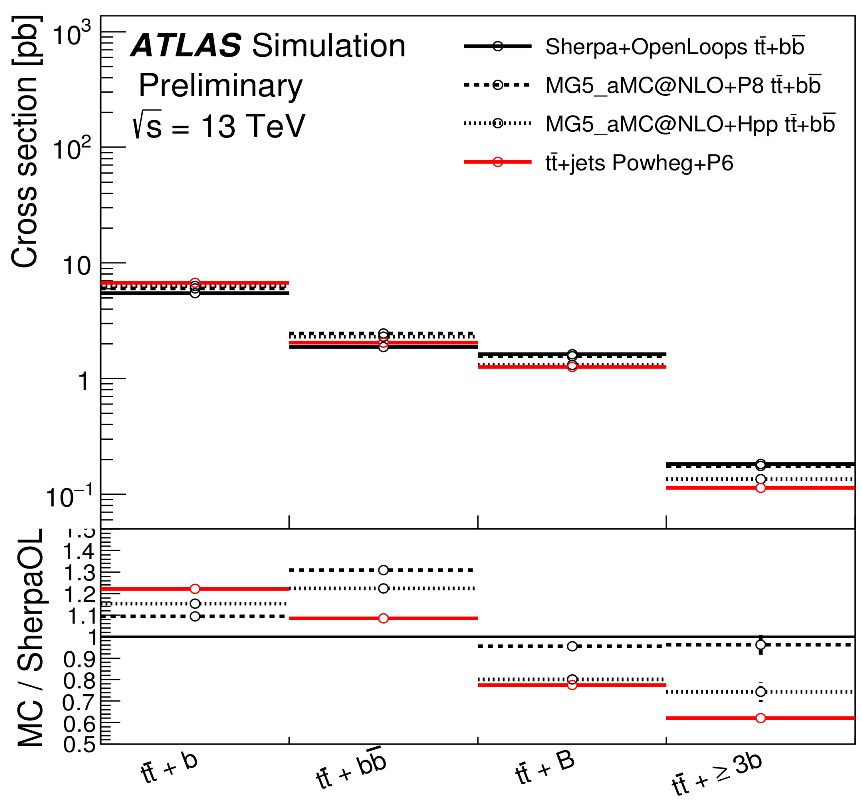




Exploit different background compositions in simultaneous fit of all regions to reduce uncertainties.

$t\bar{t}H(bb)$ analysis: $t\bar{t}$+jets background modelling

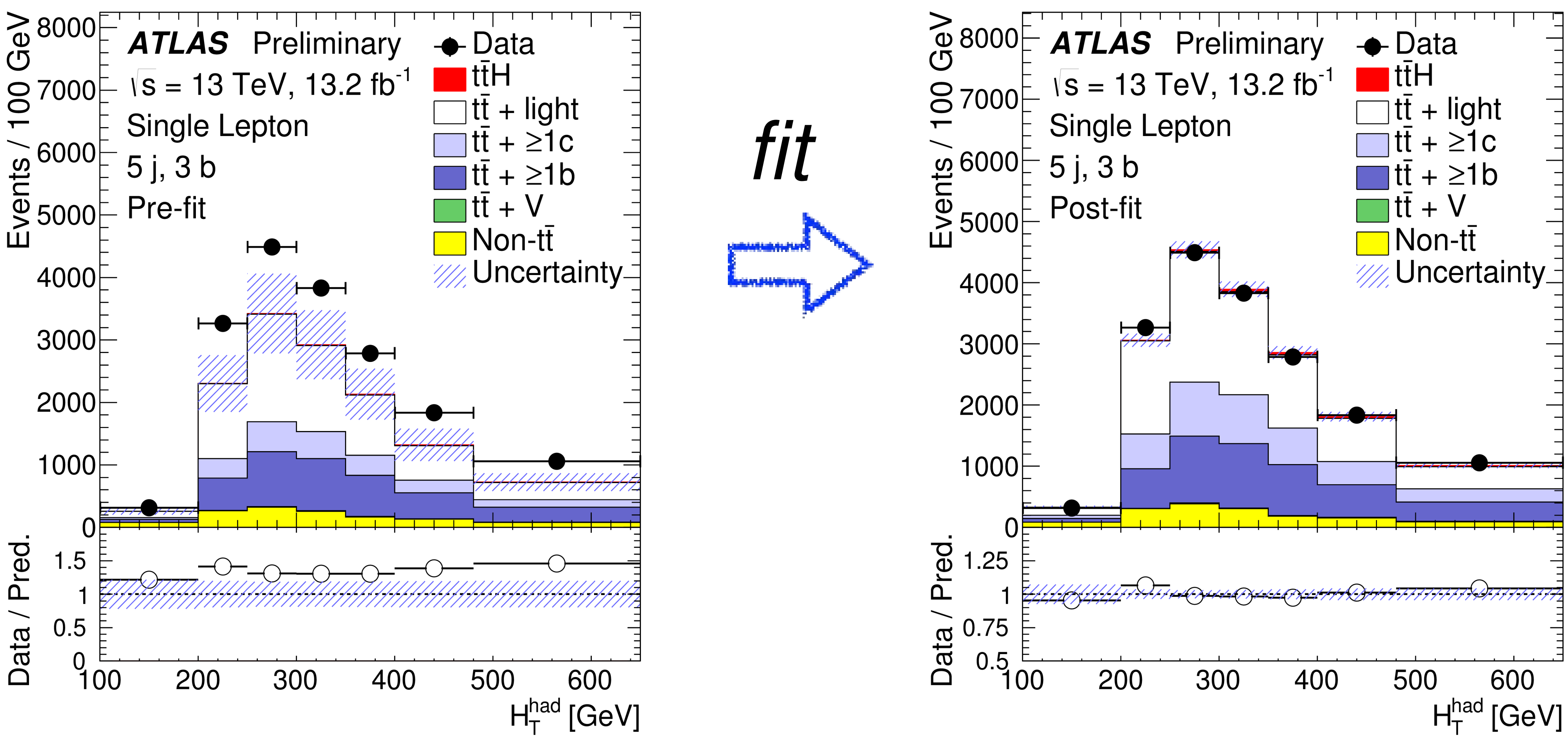
- Estimating $t\bar{t}$+jets critical part of analysis: use Powheg+Pythia6 NLO simulation, with top and $t\bar{t}$ p_T spectra corrected to NNLO calculation.
- $t\bar{t}$ + ≥1 b-jet corrected to 4-flavour scheme NLO $t\bar{t}$+bb calculation with Sherpa+OpenLoops.
- Normalization of $t\bar{t}$ + ≥1 b-jet and $t\bar{t}$ + ≥1 c-jet backgrounds taken as free parameters in the fit to data.
- Many sources of uncertainty considered, including choice of generator, parton shower and hadronisation model, PDF, and initial and final-state radiation.



Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.53	−0.53
Jet flavour tagging	+0.26	−0.26
$t\bar{t}H$ modelling	+0.32	−0.20
Background model statistics	+0.25	−0.25
$t\bar{t}+\geq 1c$ modelling	+0.24	−0.23
Jet energy scale and resolution	+0.19	−0.19
$t\bar{t}$+light modelling	+0.19	−0.18
Other background modelling	+0.18	−0.18
Jet-vertex association, pileup modelling	+0.12	−0.12
Luminosity	+0.12	−0.12
$t\bar{t}Z$ modelling	+0.06	−0.06
Light lepton (e,μ) ID, isolation, trigger	+0.05	−0.05
Total systematic uncertainty	+0.90	−0.75
$t\bar{t}+\geq 1b$ normalisation	+0.34	−0.34
$t\bar{t}+\geq 1c$ normalisation	+0.14	−0.14
Statistical uncertainty	+0.49	−0.49
Total uncertainty	+1.02	−0.89

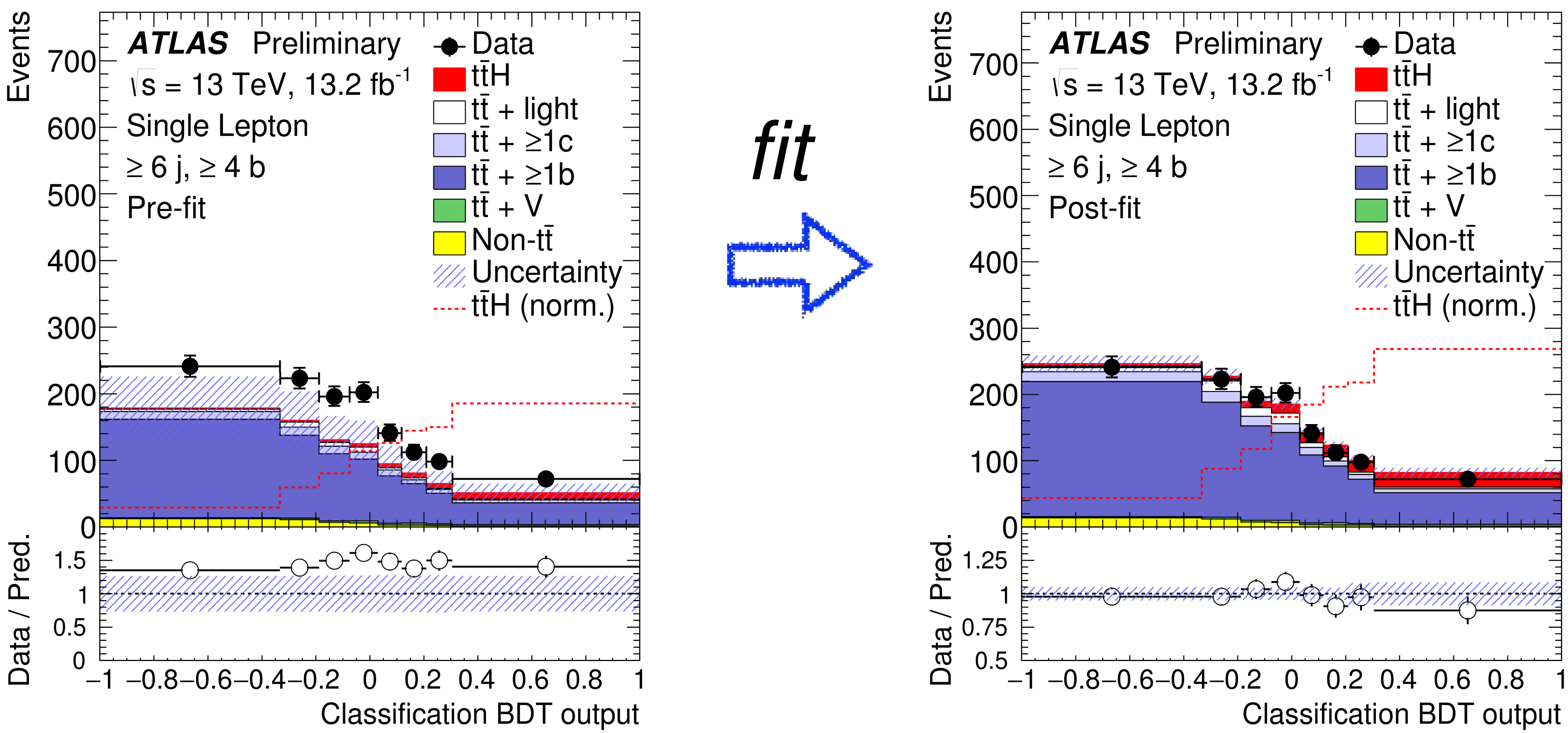
$t\bar{t}H(bb)$ analysis: discriminating variables

- In control regions: the scalar sum of all jets (and the leptons) in single- (di-) lepton channel $H_{\mathrm{T}}^{\mathrm{had}}$ ($H_{\mathrm{T}}^{\mathrm{all}}$) is used as discriminating variable.
- In signal regions use two-stage multivariate technique:
  - Match observed jets to Higgs and top quarks.
  - Classify event as more signal- or background-like: BDT or NN output.



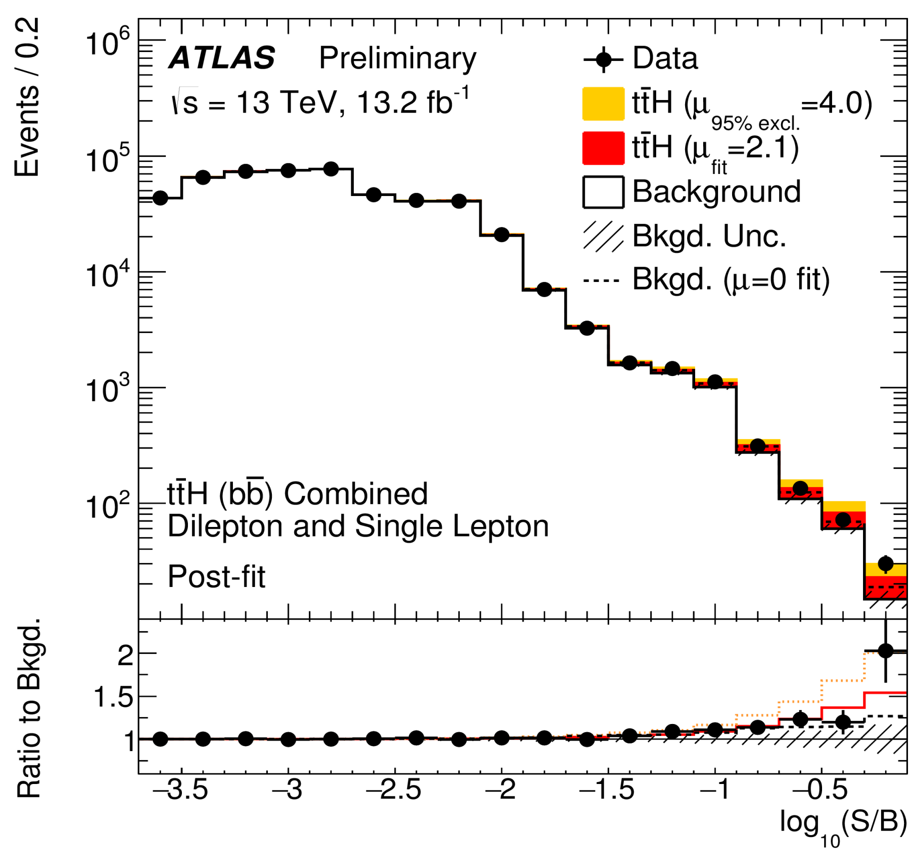
$t\bar{t}H(bb)$ analysis: discriminating variables

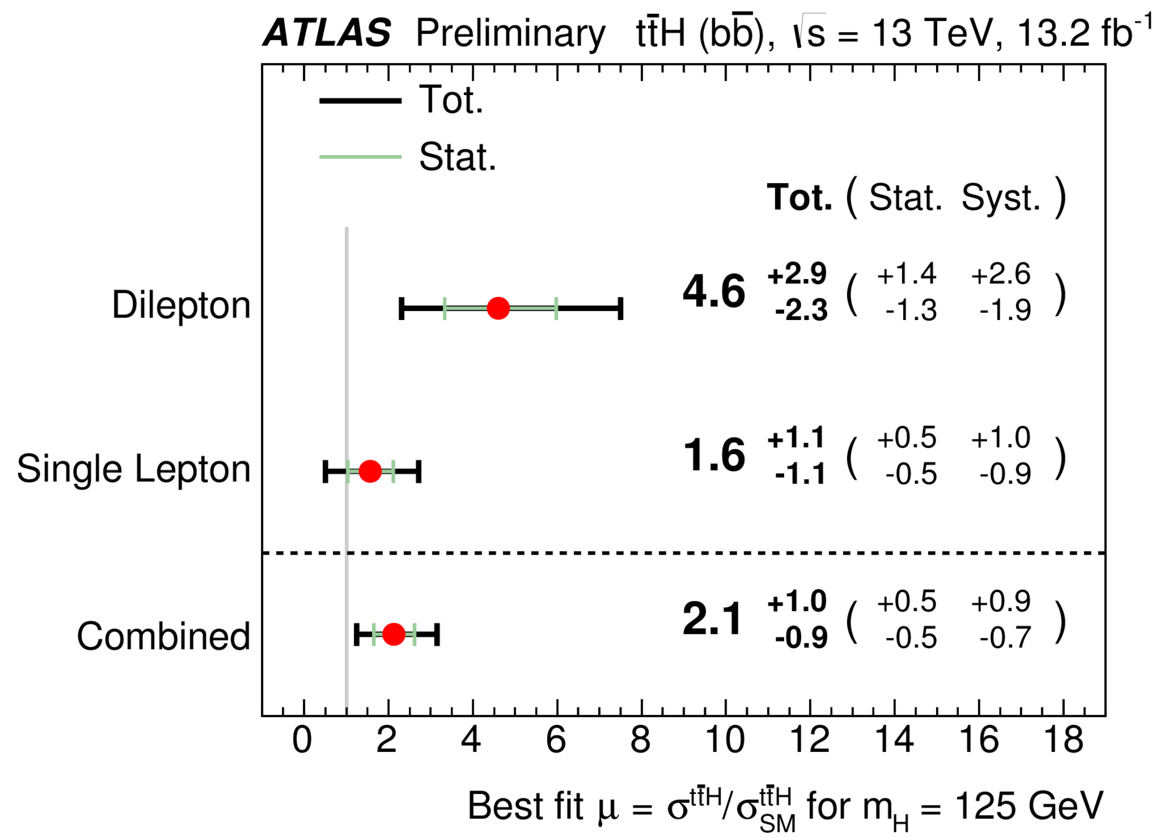
- In control regions: the scalar sum of all jets (and the leptons) in single- (di-) lepton channel H_T^{had} (H_T^{all}) is used as discriminating variable.
- In signal regions use two-stage multivariate technique:
  - Match observed jets to Higgs and top quarks.
  - Classify event as more signal- or background-like: BDT or NN output.



$t\bar{t}H(bb)$ analysis: result

- Data vs. prediction in all analysis bins, ranked by S/B → left plot.
- Summary of signal strength measurements → right plot.
- 95% C.L. upper limit on the $t\bar{t}H$ signal strength → bottom table.





	Observed	Expected ($\mu = 0$) Median	+/-1σ	+/-2σ	Expected ($\mu = 1$)
Dilepton	10.1	5.3	[3.8, 7.9]	[2.8, 12.6]	6.0
Single lepton	3.6	2.2	[1.6, 3.2]	[1.2, 4.7]	2.9
Combined	4.0	1.9	[1.4, 2.8]	[1.0, 4.2]	2.7

Uncertainty of the measurement is dominated by normalization and modelling of $t\bar{t}$ + b/c-jet backgrounds.

Search for the $t\bar{t}H$ (multileptons) process

ATLAS-CONF-2016-058

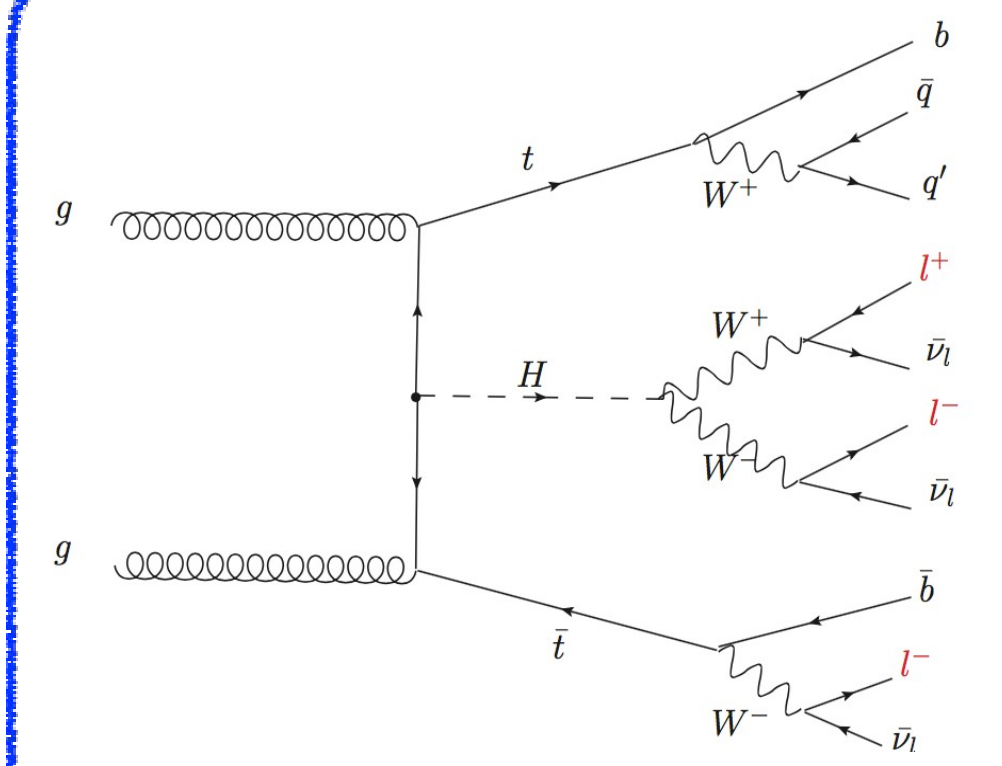
- $t\bar{t}H$ cross section at 13 TeV is 507 fb → 1% of total Higgs production cross section.

- Search for the $t\bar{t}H$ production in many Higgs decay modes (branching ratio ~ 89%).

Higgs decay mode	Branching ratio [%]
H→ bb	58.1
H→ WW	21.5
H→ ττ	6.3
H→ ZZ	2.6
H→ γγ	0.23

$t\bar{t}H$(multileptons) channel has many possible final states → focus on those with clean signature and low backgrounds.

$t\bar{t}H$(multileptons) Feynman diagram



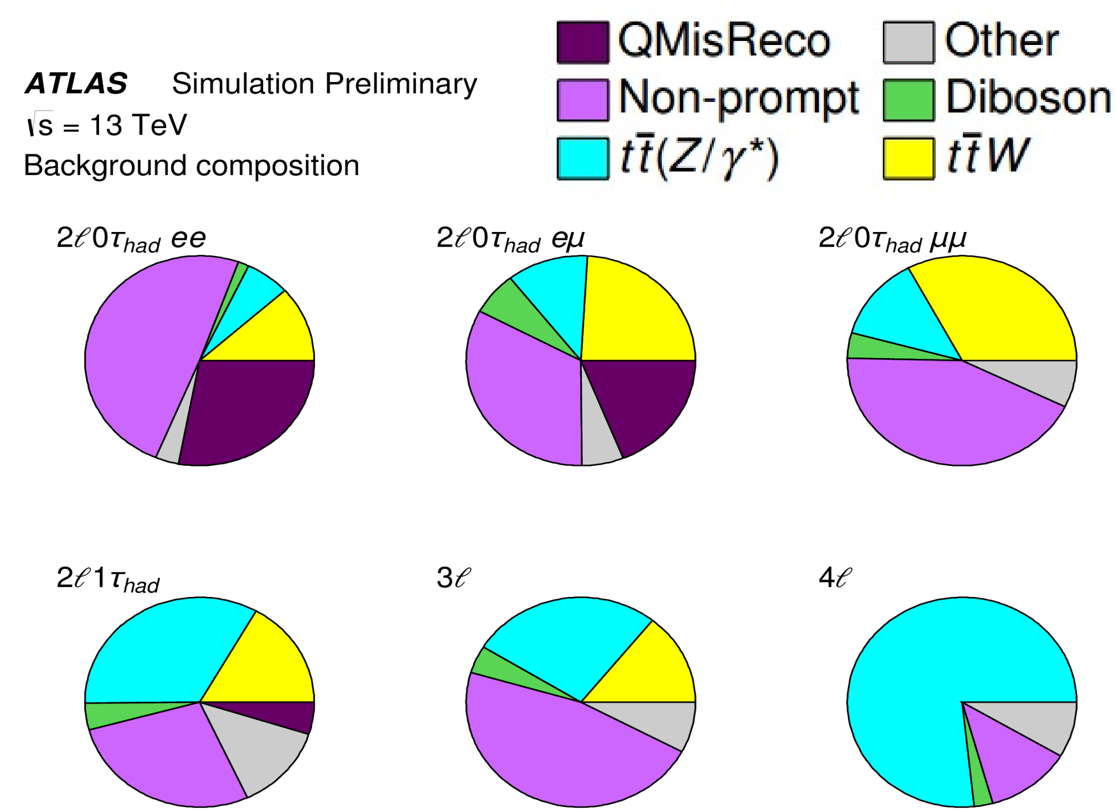
H→WW, 3-leptons

$t\bar{t}H$ (multileptons) analysis: event selection and background

- Events are separated into 4 orthogonal channels:
  - two same-charge light leptons + no τ_{had} → $2\ell 0\tau_{had}$
    (at least 5 jets and at least 1 b-jet)
  - two same-charge light leptons + one τ_{had} → $2\ell 1\tau_{had}$
    (at least 4 jets and at least 1 b-jet)
  - three light leptons → 3ℓ (≥ 4jets, ≥ 1bjet, or 3jets, ≥ 2bjets)
  - four light leptons → 4ℓ (≥ 2jets, ≥ 1bjet)

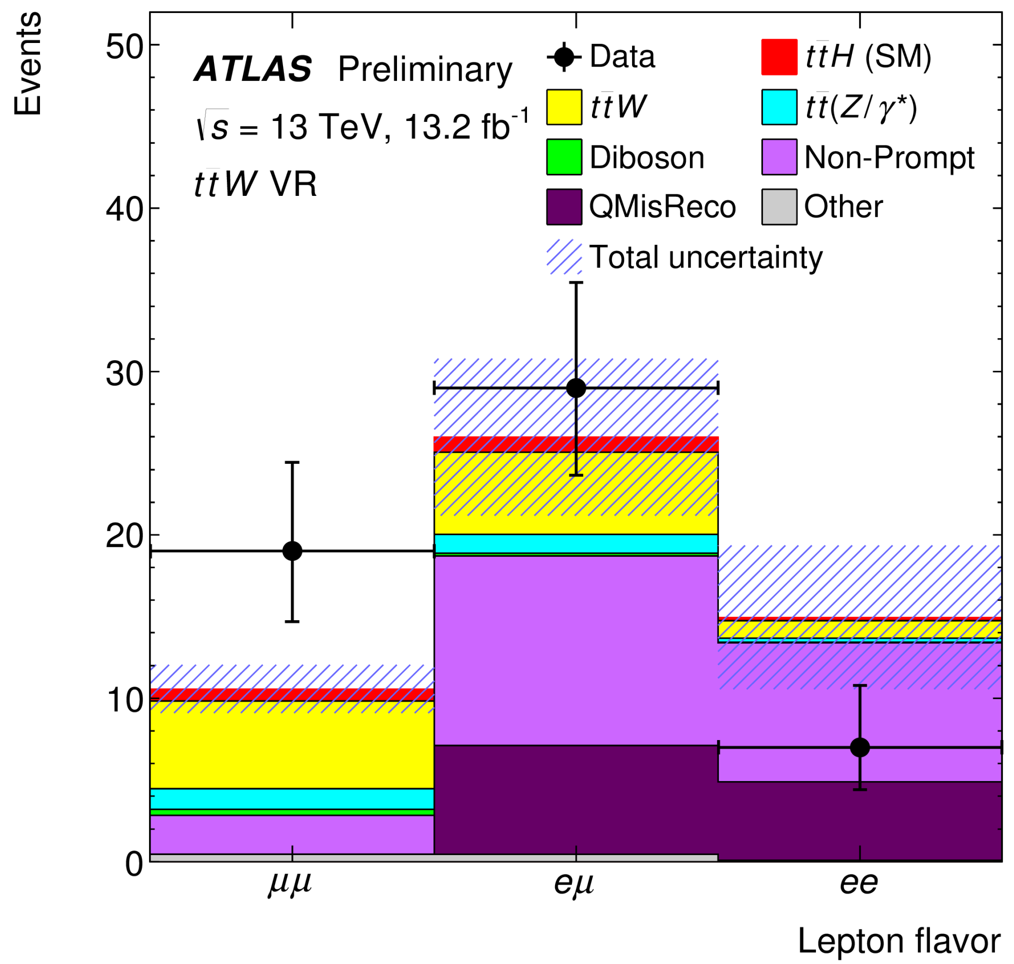
	Higgs boson decay mode				$A \times \epsilon$
Category	WW^*	$\tau\tau$	ZZ^*	Other	$(\times 10^{-4})$
$2\ell 0\tau_{had}$	77%	17%	3%	3%	14
$2\ell 1\tau_{had}$	46%	51%	2%	1%	2.2
3ℓ	74%	20%	4%	2%	9.2
4ℓ	72%	18%	9%	2%	0.88

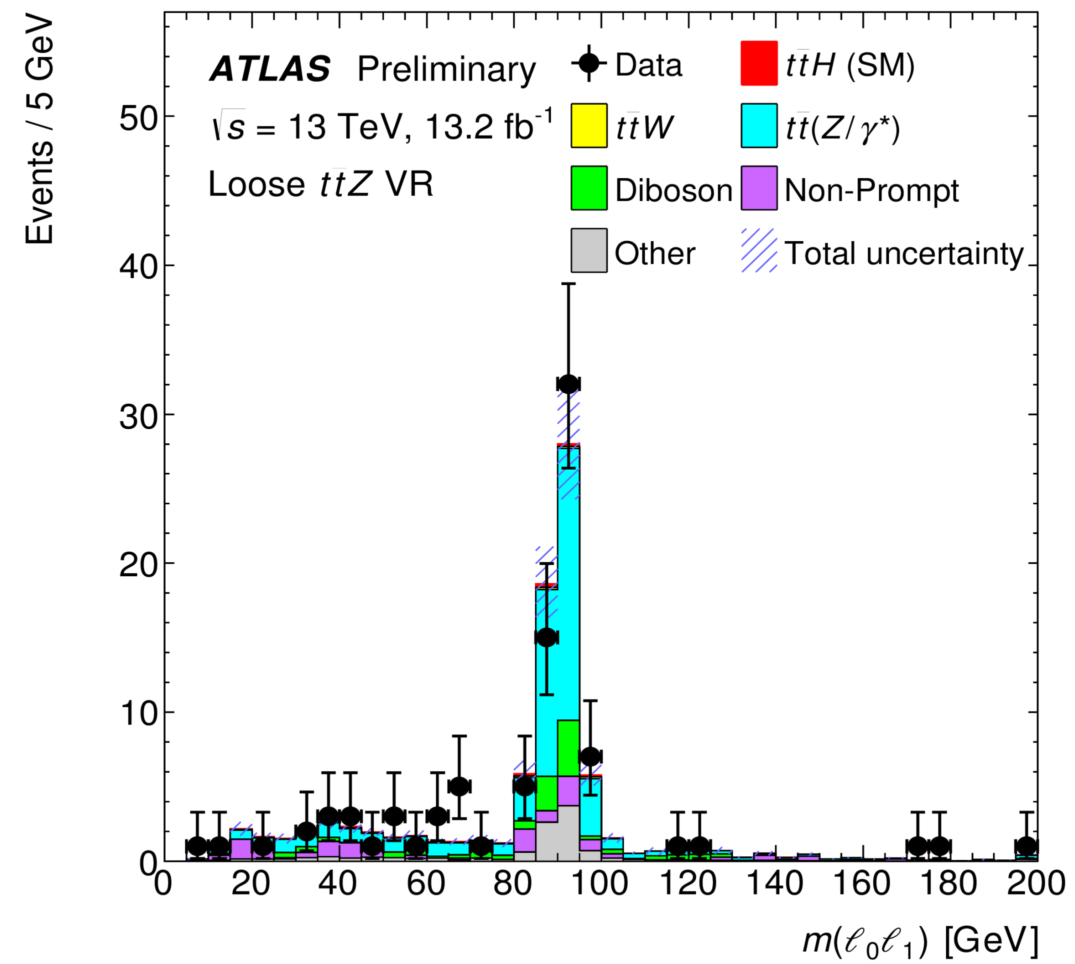
- Dominant backgrounds:
  - $t\bar{t}W$, $t\bar{t}Z$ → estimated from simulation
  - di-boson (VV) → estimated from simulation
  - non-prompt light leptons → estimated from data control region
  - electron charge mis-identification → estimated from data of Z+jets events
  - hadronic tau mis-reconstruction → estimated from simulation and normalised to data control region.



$t\bar{t}H$ (multileptons) analysis: validation regions

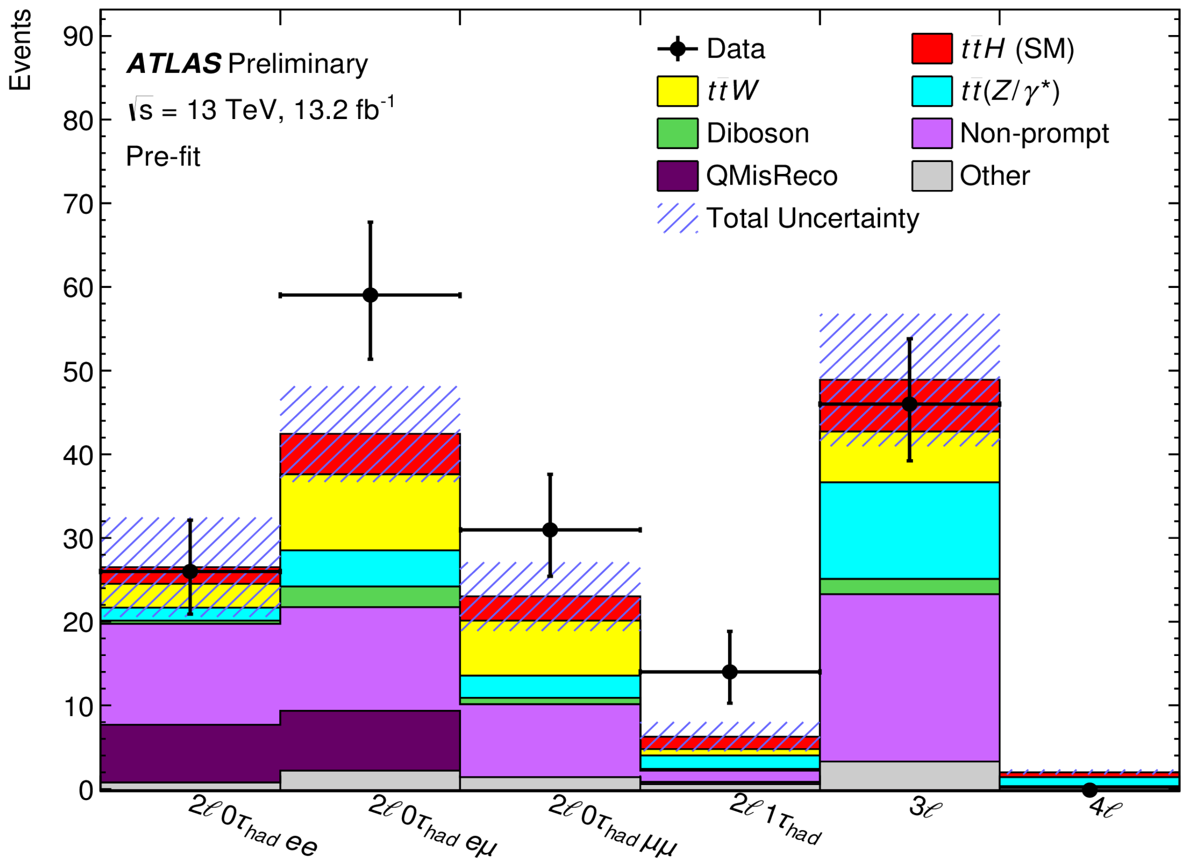
- Validation plot for control region of
  - $t\bar{t}W$ (left plot): selection close to the $2\ell 0\tau_{had}$ signal region, but with low jet multiplicity.
  - $t\bar{t}Z$ (right plot): selection close to the 3ℓ signal region, but within Z mass window.

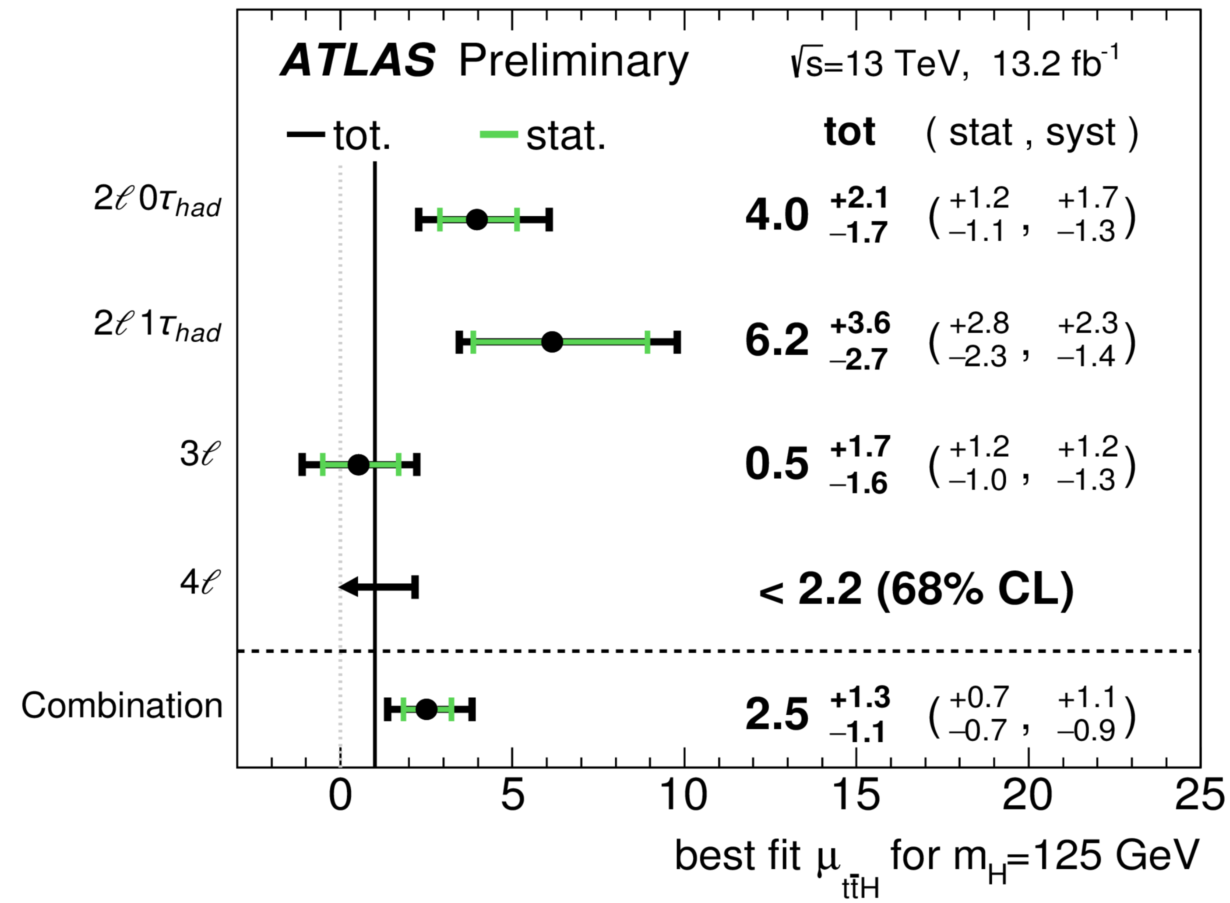




$t\bar{t}H$ (multileptons) analysis: result

- Cut-and-count analysis in 6 categories: $2\ell 0\tau_{had}$ ($ee, e\mu, \mu\mu$), $2\ell 1\tau_{had}$, 3ℓ and 4ℓ.
  - Pre-fit predictions and observed data events.
  - Best fit values of the $t\bar{t}H$ signal strength.





Systematic uncertainty is dominated by non-prompt background estimates in the $2\ell 0\tau_{had}$, $2\ell 1\tau_{had}$, and 3ℓ channels.

Search for the $t\bar{t}H$ ($H\to\gamma\gamma$) process

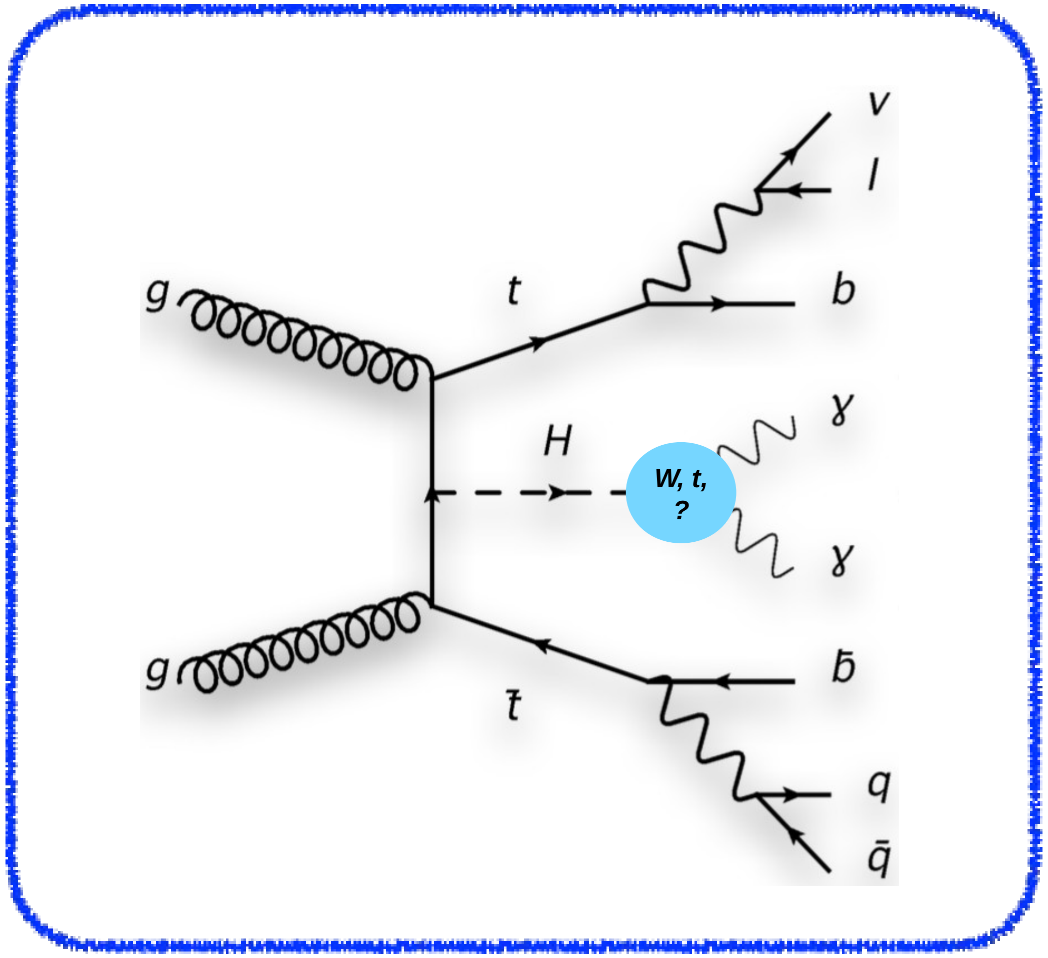
ATLAS-CONF-2016-067

- $t\bar{t}H$ cross section at 13 TeV is 507 fb → 1% of total Higgs production cross section.
- Search for the $t\bar{t}H$ production in many Higgs decay modes (branching ratio ~ 89%).

Higgs decay mode	Branching ratio [%]
$H\to bb$	58.1
$H\to WW$	21.5
$H\to \tau\tau$	6.3
$H\to ZZ$	2.6
$H\to \gamma\gamma$	0.23

$t\bar{t}H(\gamma\gamma)$ channel exploits the excellent diphoton mass resolution of the Higgs peak over its continuum background.

$t\bar{t}H(\gamma\gamma)$ Feynman diagram



$t\bar{t}H$ (γγ) analysis: event selection

- Events must have two tight, isolated photons, and

Leptonic channel
(tt leptonic decay)

- at least one light lepton
- at least 2 jets
- at least 1 b-tagged jet
- Z veto ($m_{\ell\ell}$ and $m_{e\gamma}$)
- Missing ET > 20 GeV for 1-tag events

hadronic channel
(tt hadronic decay)

- no light lepton
- at least 5 jets
- at least 1 b-tagged jet

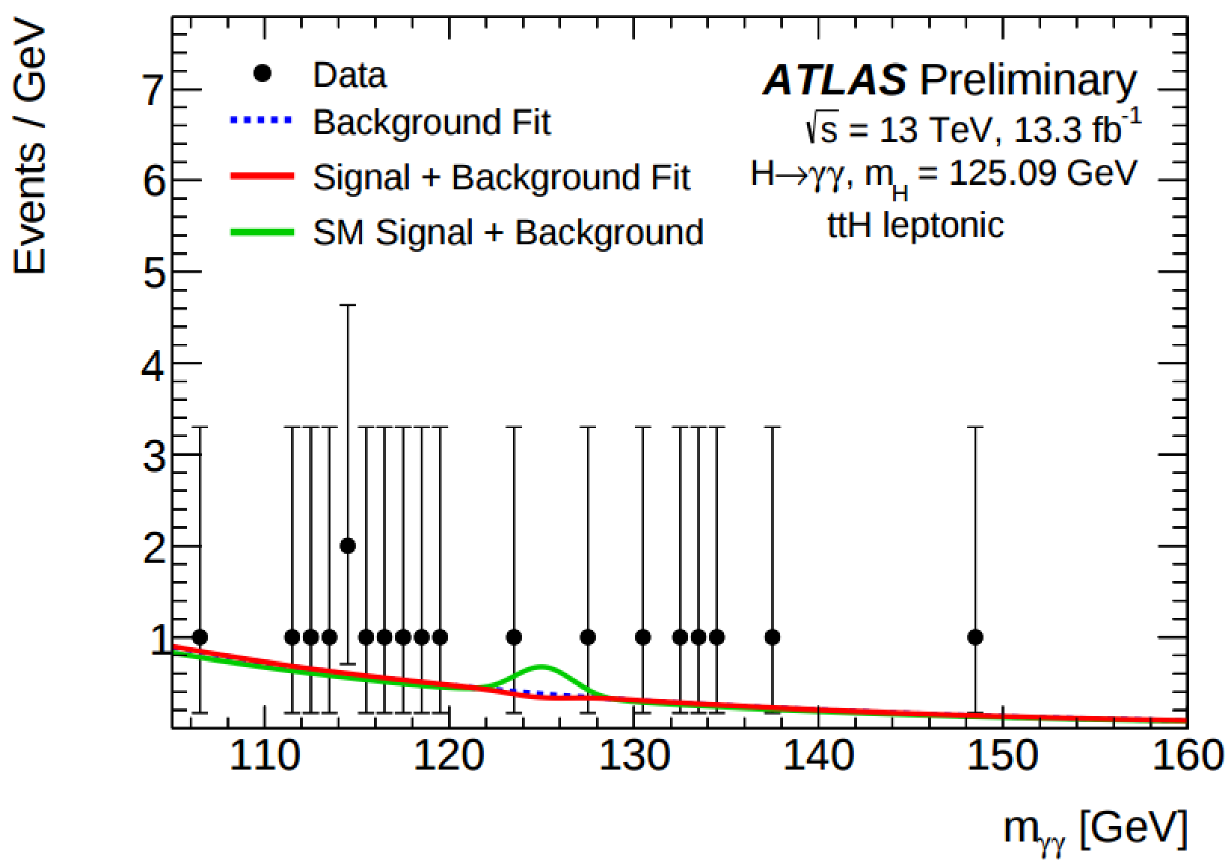
- Photon pair invariant mass is used as discriminanting variable.

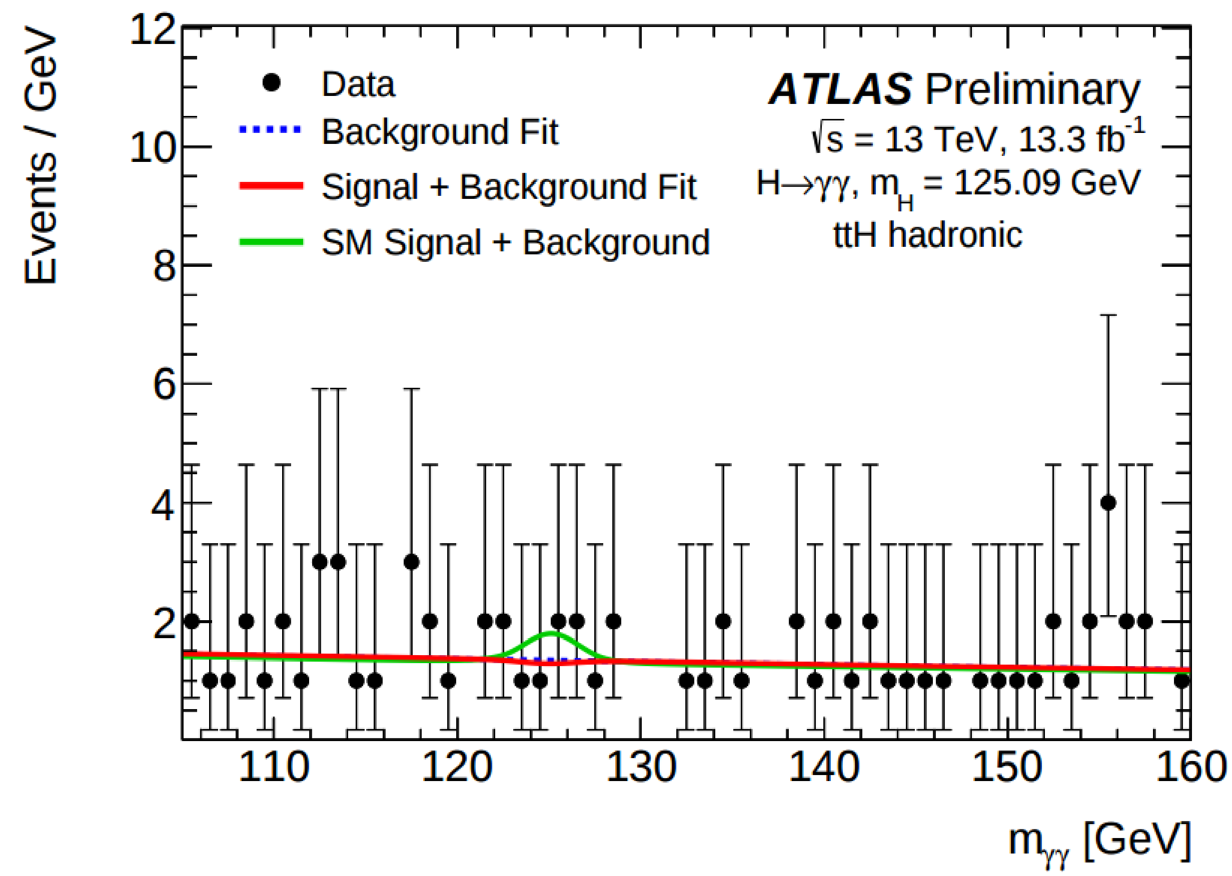
Channel	Region	$t\bar{t}H$ (S)	Bkgd (B)	$tHjb + WtH$	S/B	N_{Data}
$H \to \gamma\gamma$	all-hadronic	1.58	8.27	0.10	0.19	9
	leptonic	1.16	2.42	0.10	0.48	2

Events in mass window containing 90% of $t\bar{t}H$ signal

$t\bar{t}H$ (γγ) analysis: result

- The dominant continuum background is estimated from an exponential form fit to the data sideband region.





- The measured $t\bar{t}H$ signal strength is :

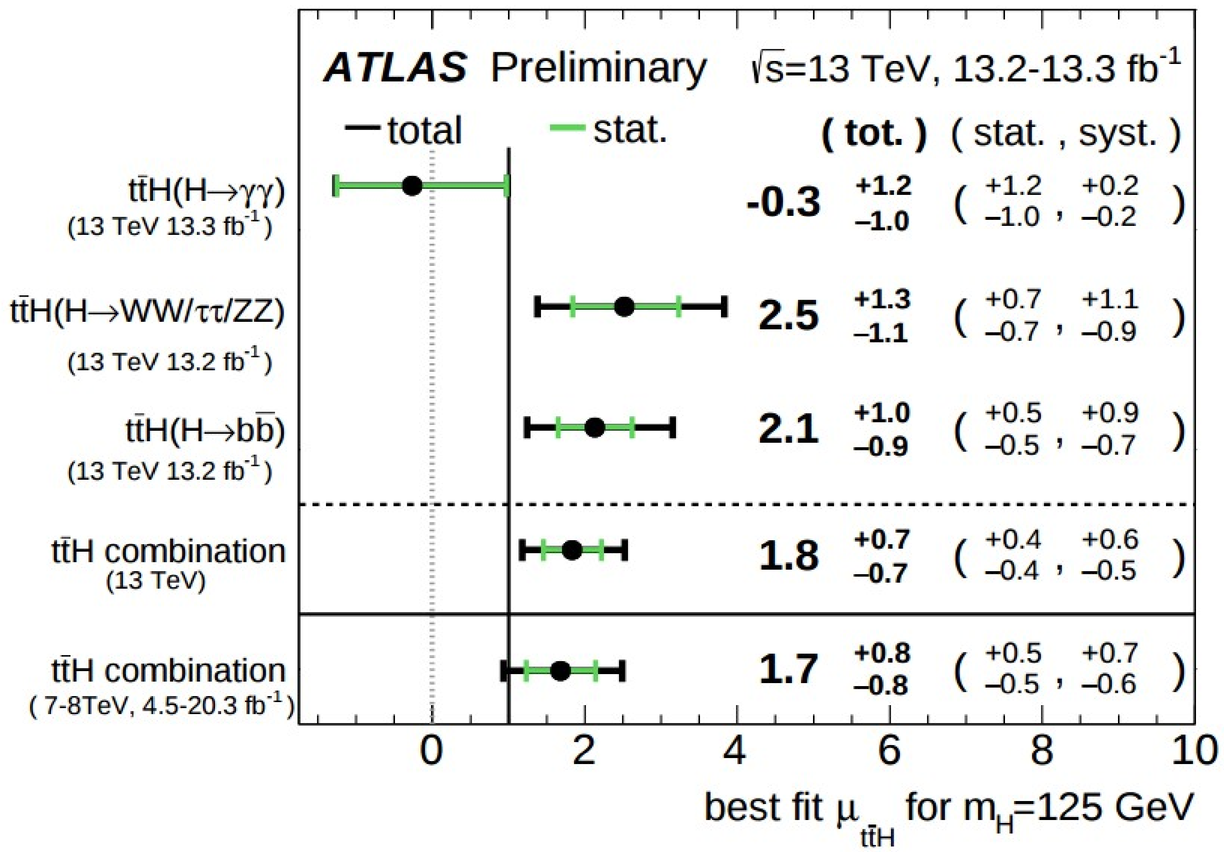
$$\mu_{t\bar{t}H} = -0.3 \,^{+1.2}_{-1.0}\,(\text{tot.})\ [\,^{+1.2}_{-1.0}\,(\text{stat.})\ ]$$

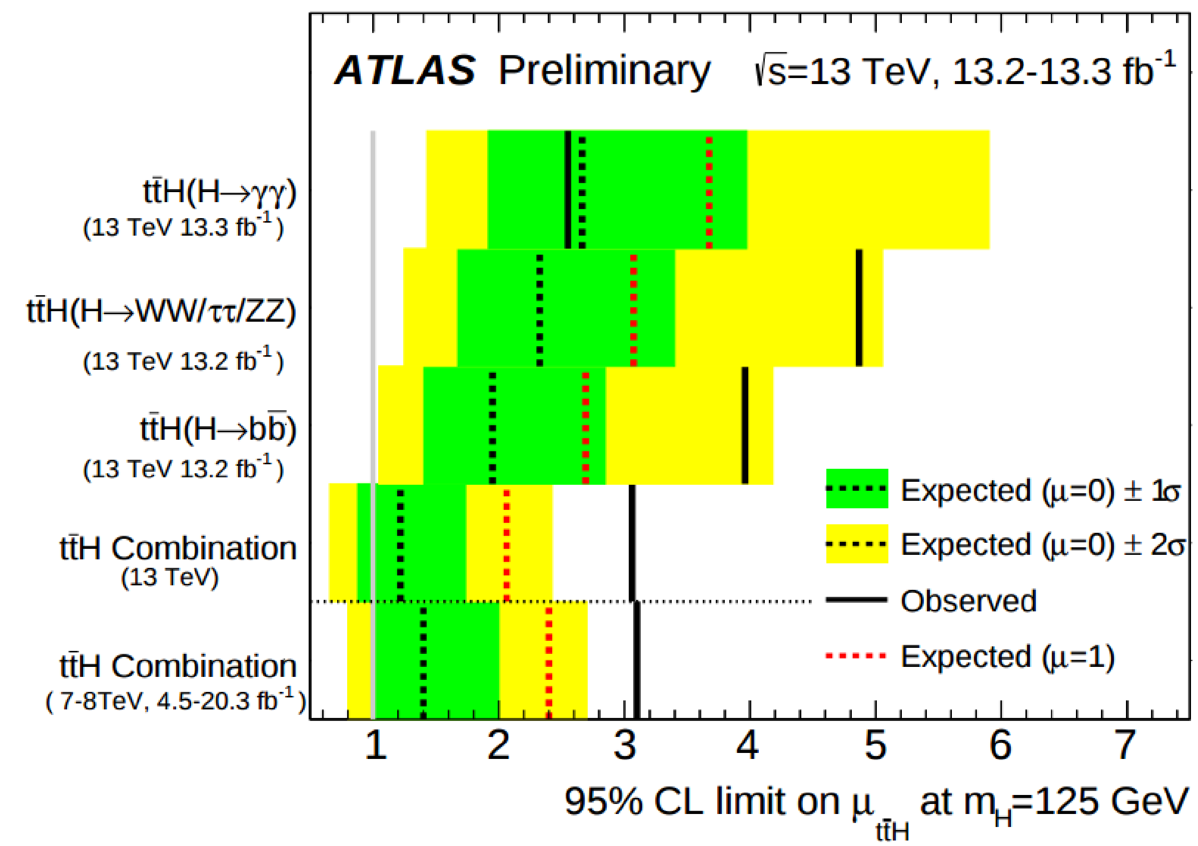
Total uncertainty is dominated by the statistical one !

$t\bar{t}$H analyses: combination

ATLAS-CONF-2016-068

- Summary of the $t\bar{t}$H signal strength measurements (left) and upper limits (right).





- Expected and observed significance with respect to background-only hypothesis.

Channel	Significance	
	Observed [σ]	Expected [σ]
$t\bar{t}H$, $H \to \gamma\gamma$	−0.2	0.9
$t\bar{t}H$, $H \to (WW, \tau\tau, ZZ)$	2.2	1.0
$t\bar{t}H$, $H \to b\bar{b}$	2.4	1.2
$t\bar{t}H$ combination	2.8	1.8

Summary

- A search for $t\bar{t}H$ production process has been performed in three channels, $t\bar{t}H$ (bb), $t\bar{t}H$ (multileptons), and $t\bar{t}H$ ($\gamma\gamma$), using 13.2 fb^{-1} - 13.3 fb^{-1} of pp collision data at $\sqrt{s}$ = 13 TeV, recorded by the ATLAS experiment.

- The best fit value of the $t\bar{t}H$ signal strength is 1.8 ± 0.7.
  - Observed significance: 2.8 sigma (1.8 expected from SM).
  - 95% CL upper limit on $t\bar{t}H$ signal strength: 3.1 (1.4 expected from bkg-only).

- Sensitivity exceeds Run 1 analyses.

- Possibility for greater precision with full 2016 dataset: Stay Tuned!

Backup Slides

$t\bar{t}$H analyses: combination

- Expected signal and post-fit background yields in each ttH search category.

Channel	Region	$t\bar{t}H$ (S)	Bkgd (B)	$tHjb + WtH$	S/B	N_{Data}
$H \to \gamma\gamma$	all-hadronic	1.58	8.27	0.10	0.19	9
	leptonic	1.16	2.42	0.10	0.48	2
$H \to (WW, \tau\tau, ZZ)$	2ℓSS ee	1.99 ± 0.51	22.2 ± 3.4	0.10 ± 0.03	0.09	26
	2ℓSS $e\mu$	4.82 ± 0.95	38.5 ± 5.1	0.26 ± 0.07	0.13	59
	2ℓSS $\mu\mu$	2.85 ± 0.58	21.2 ± 3.8	0.15 ± 0.04	0.13	31
	2ℓSS $+\tau_{had}$	1.43 ± 0.31	5.7 ± 1.7	0.11 ± 0.03	0.25	14
	3ℓ	6.2 ± 1.1	38.9 ± 5.3	0.30 ± 0.08	0.16	46
	4ℓ	0.59 ± 0.10	1.42 ± 0.24	0.014 ± 0.006	0.42	0
$H \to b\bar{b}$	ℓ+jets ($\geq$ 6j,3bj)	119 ± 16	11250 ± 240	6.2 ± 1.5	0.011	11561
	ℓ+jets (5j,$\geq$ 4bj)	11.8 ± 2.6	429 ± 28	0.91 ± 0.14	0.028	418
	ℓ+jets ($\geq$ 6j,$\geq$ 4bj)	44.9 ± 9.4	1191 ± 55	2.10 ± 0.50	0.038	1285
	dilepton ($\geq$ 4j,3bj)	20.6 ± 4.2	1423 ± 45	0.71 ± 0.20	0.014	1467
	dilepton ($\geq$ 4j,$\geq$ 4bj)	6.6 ± 2.0	133 ± 12	0.171 ± 0.053	0.050	154

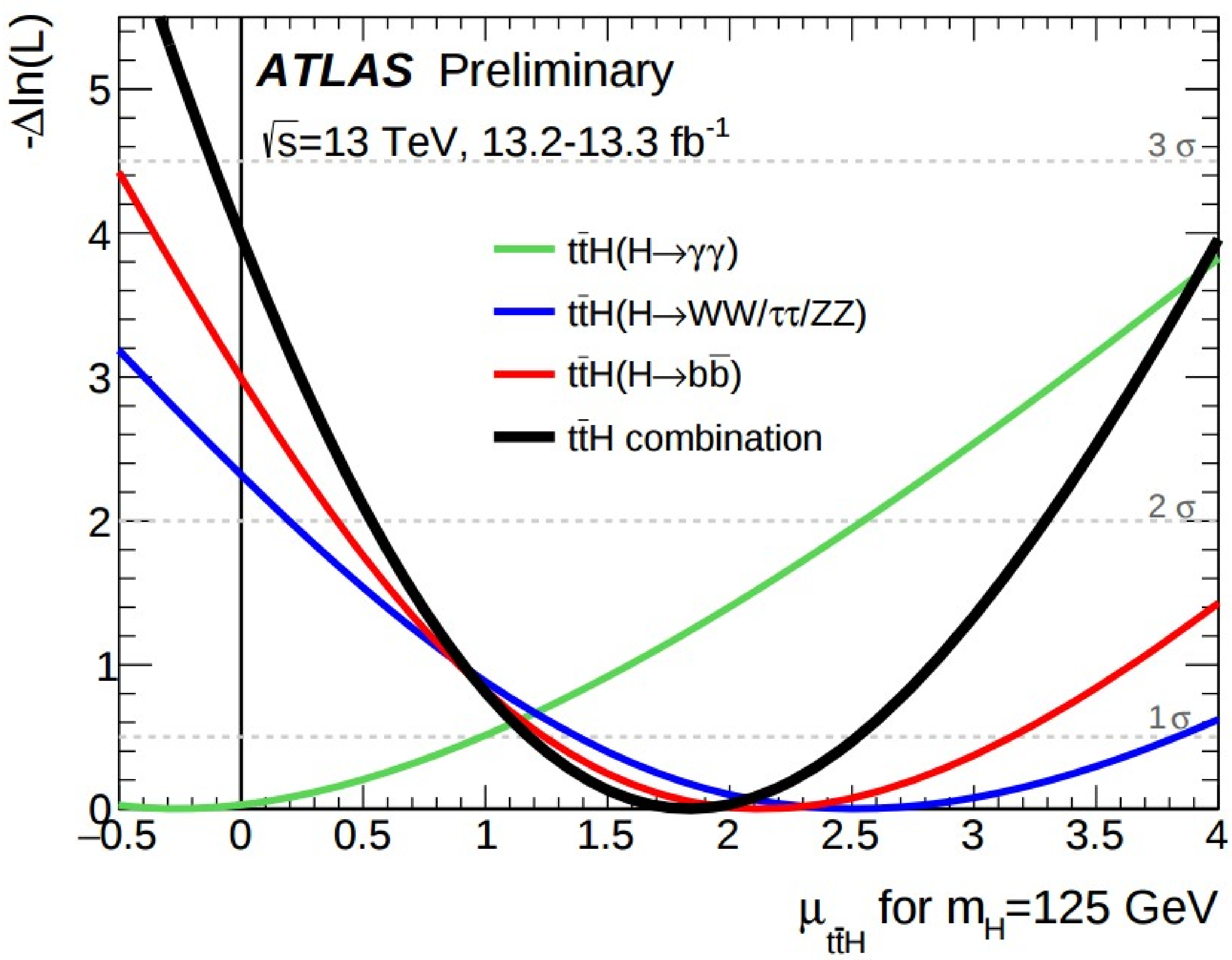
Higgs boson cross section and decay widths as a function of coupling modifiers (***κ***)

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t\kappa_b$
$\sigma(VBF)$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z\kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t\kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t\kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($B_{BSM} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Contribution of each Higgs decay in the most sensitive signal regions

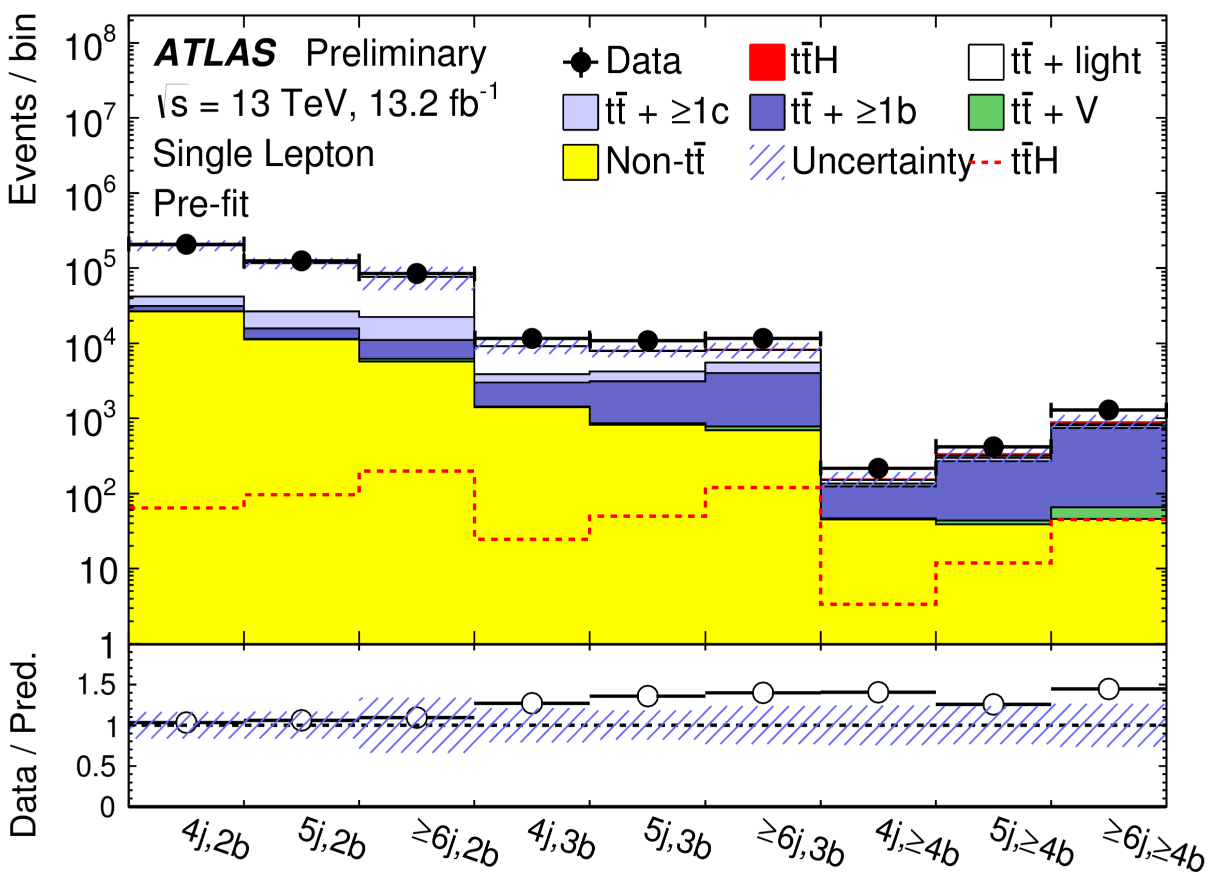
Channel	Region	WW	$\tau\tau$	ZZ	$b\bar{b}$	$\gamma\gamma$
$H \to \gamma\gamma$	all-hadronic	–	–	–	–	100%
	leptonic	–	–	–	–	100%
$H \to (WW, \tau\tau, ZZ)$	2ℓSS ee	76%	17%	2%	4%	–
	2ℓSS $e\mu$	77%	17%	3%	3%	–
	2ℓSS $\mu\mu$	79%	17%	3%	1%	–
	2ℓSS $+\tau_{\text{had}}$	46%	51%	2%	1%	–
	3ℓ	74%	20%	4%	1%	–
	4ℓ	72%	18%	9%	–	–
$H \to b\bar{b}$	ℓ+jets ($\geq$ 6j,3bj)	5%	1%	1%	90%	–
	ℓ+jets (5j,$\geq$ 4bj)	–	–	–	99%	–
	ℓ+jets ($\geq$ 6j,$\geq$ 4bj)	1%	–	1%	97%	–
	dilepton ($\geq$ 4j,3bj)	6%	1%	1%	90%	–
	dilepton ($\geq$ 4j,$\geq$ 4bj)	–	–	–	98%	–

$t\bar{t}H$ combination: Log-likelihood scores

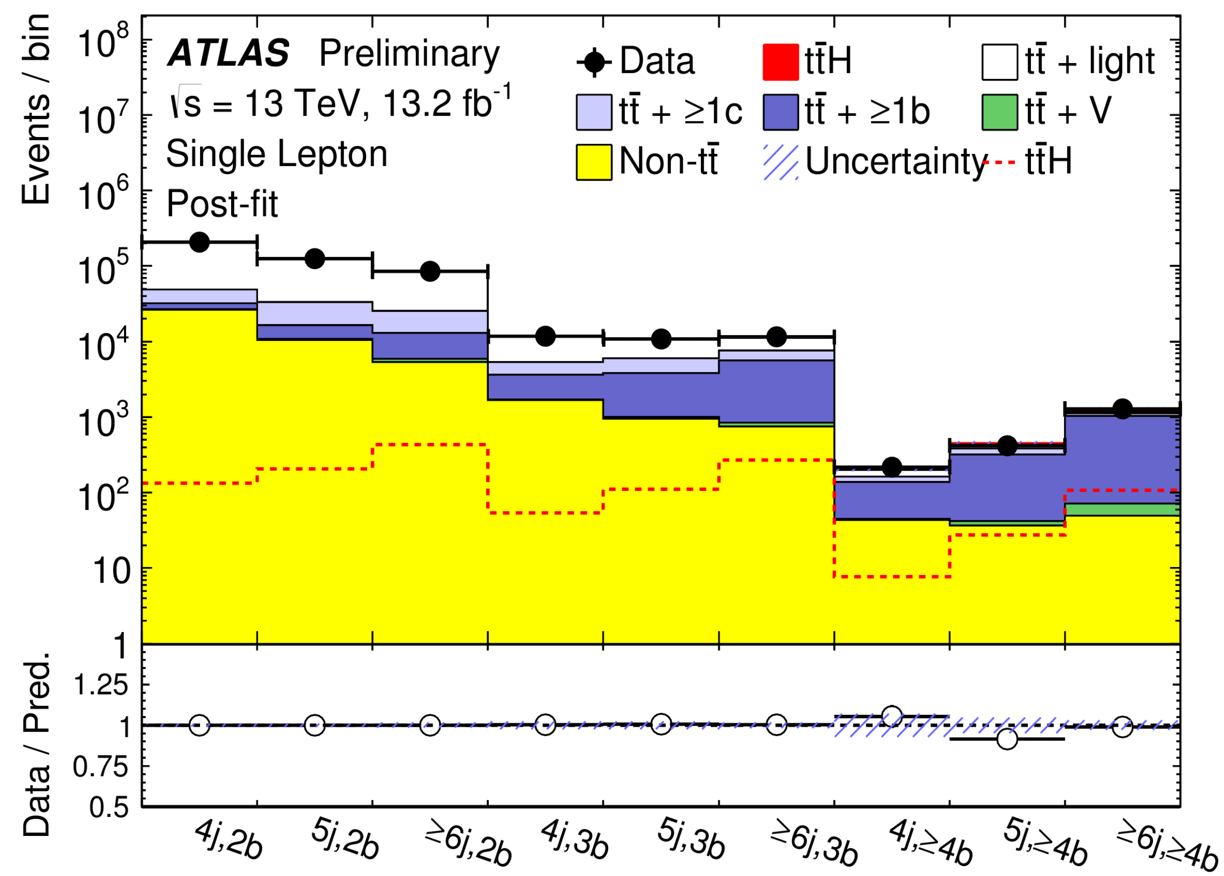


$t\bar{t}H(bb)$ single lepton regions

Pre-fit

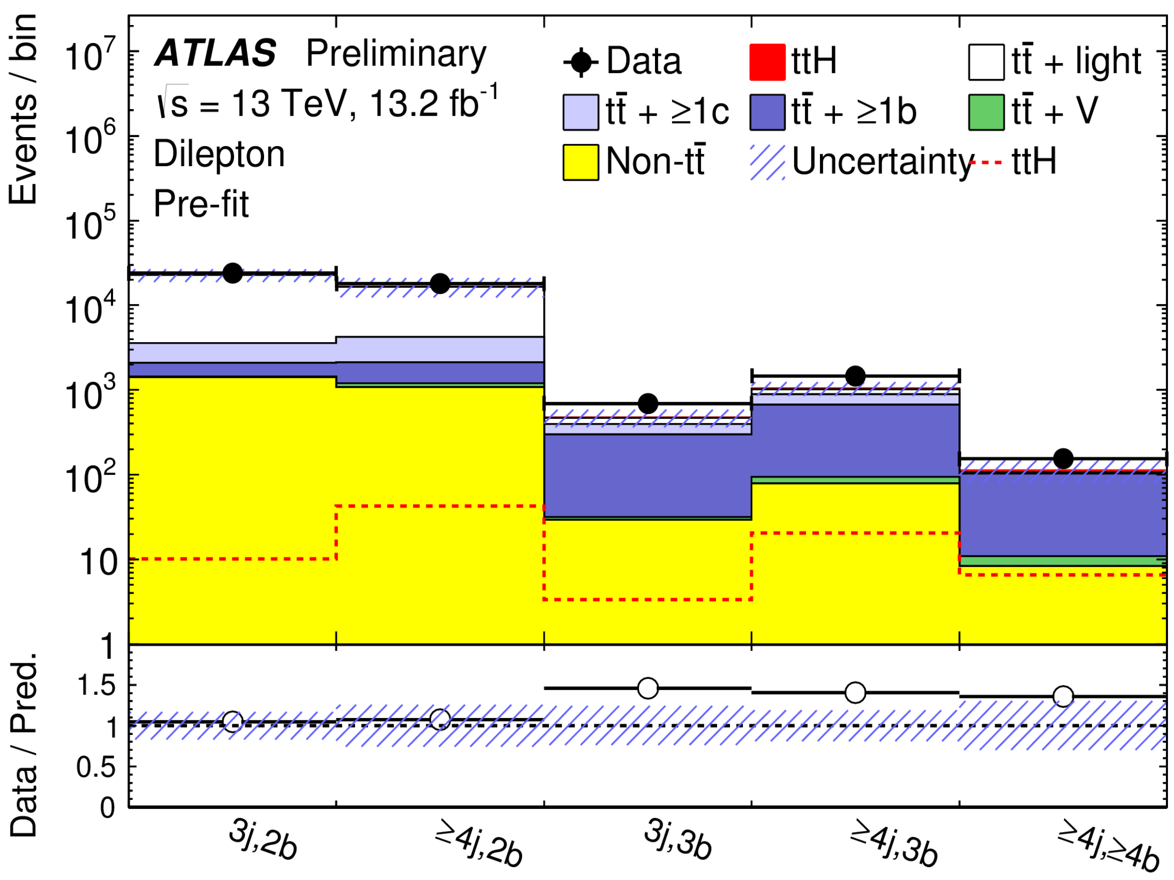


Post-fit

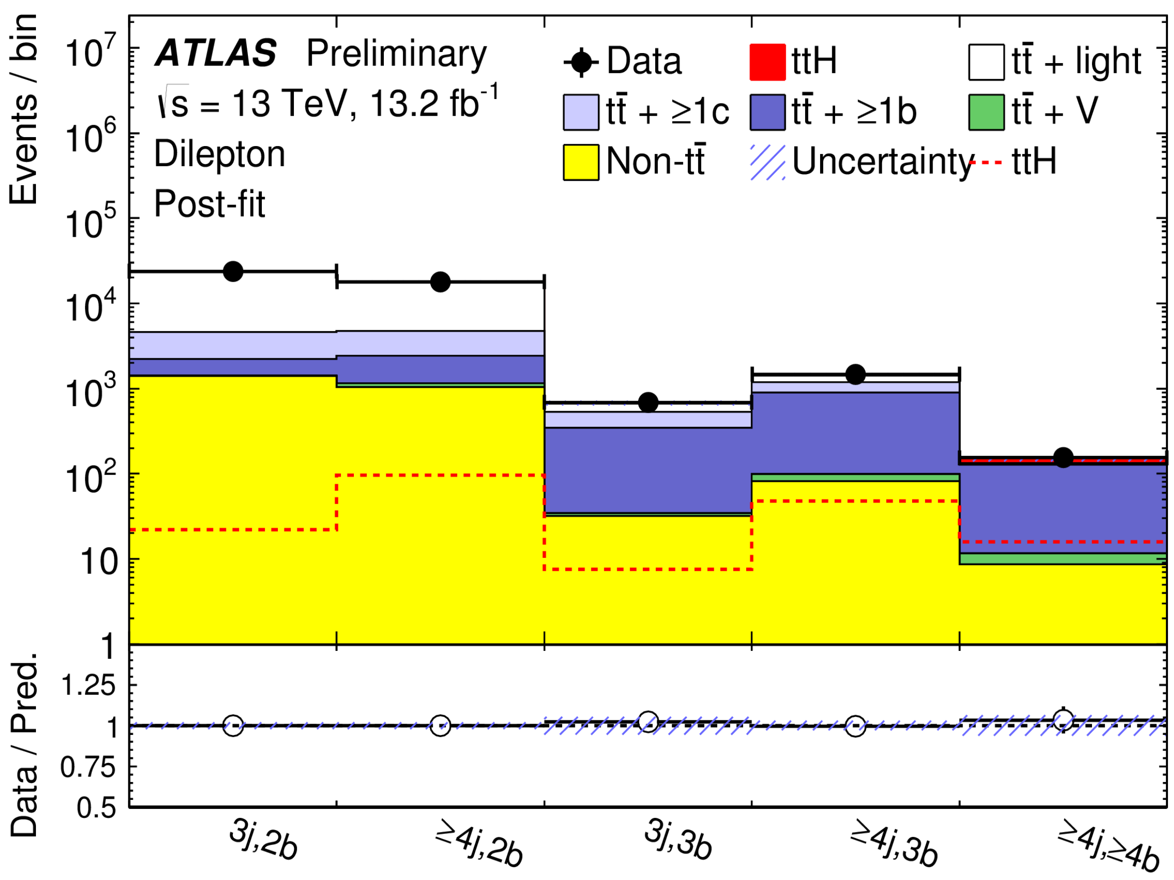


$t\bar{t}H(bb)$ dilepton regions

Pre-fit

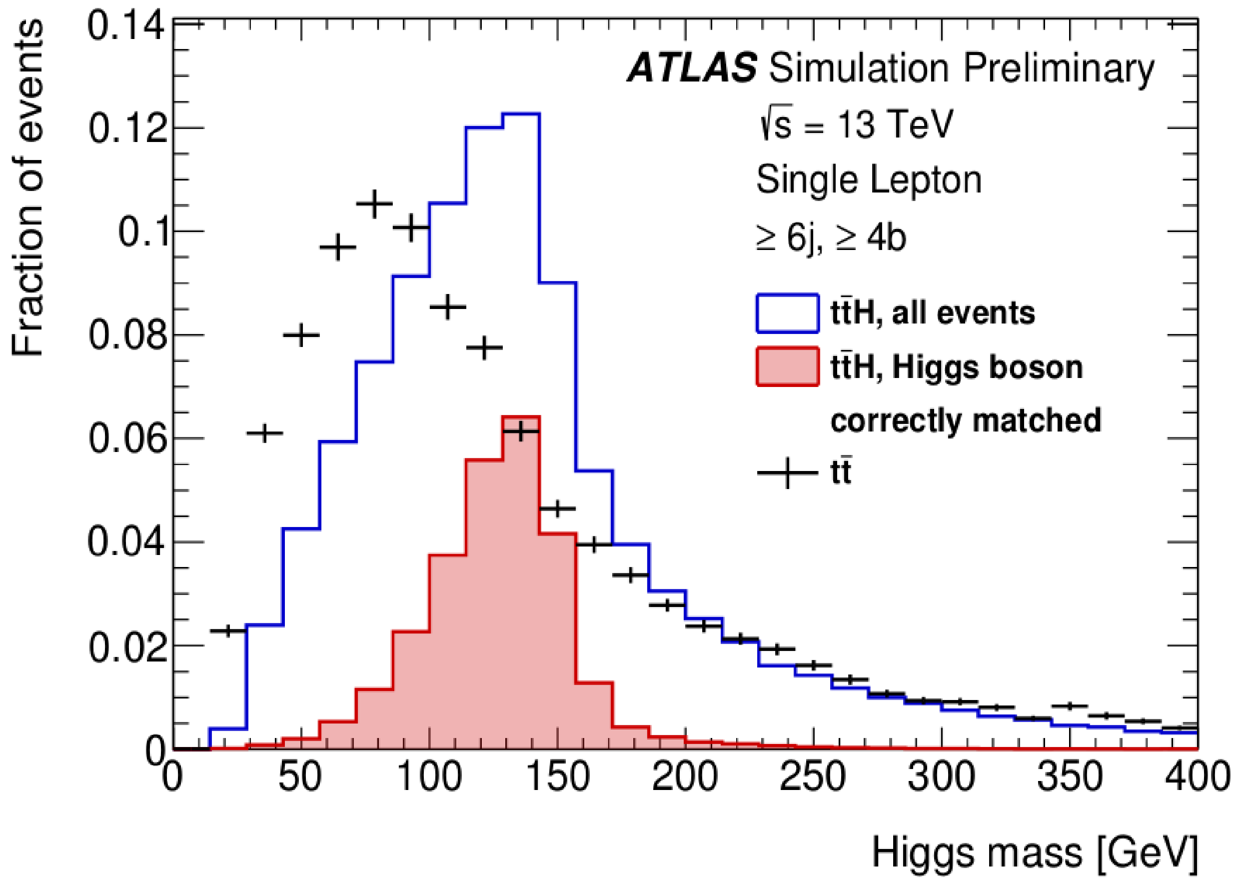


Post-fit

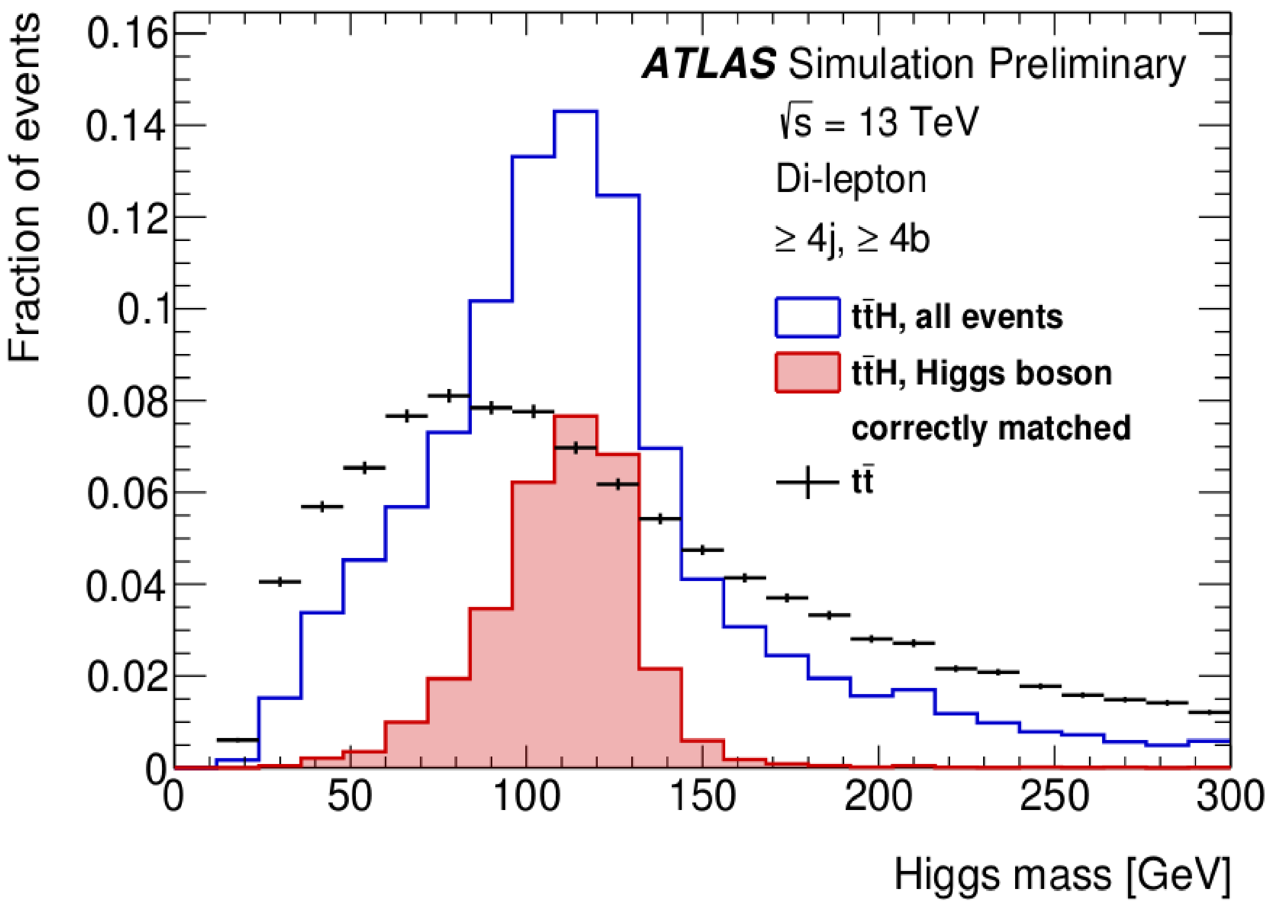


$t\bar{t}H(bb)$ mass reconstruction

Single lepton



Dilepton



$t\bar{t}H(bb)$ $t\bar{t}$+jets simulation

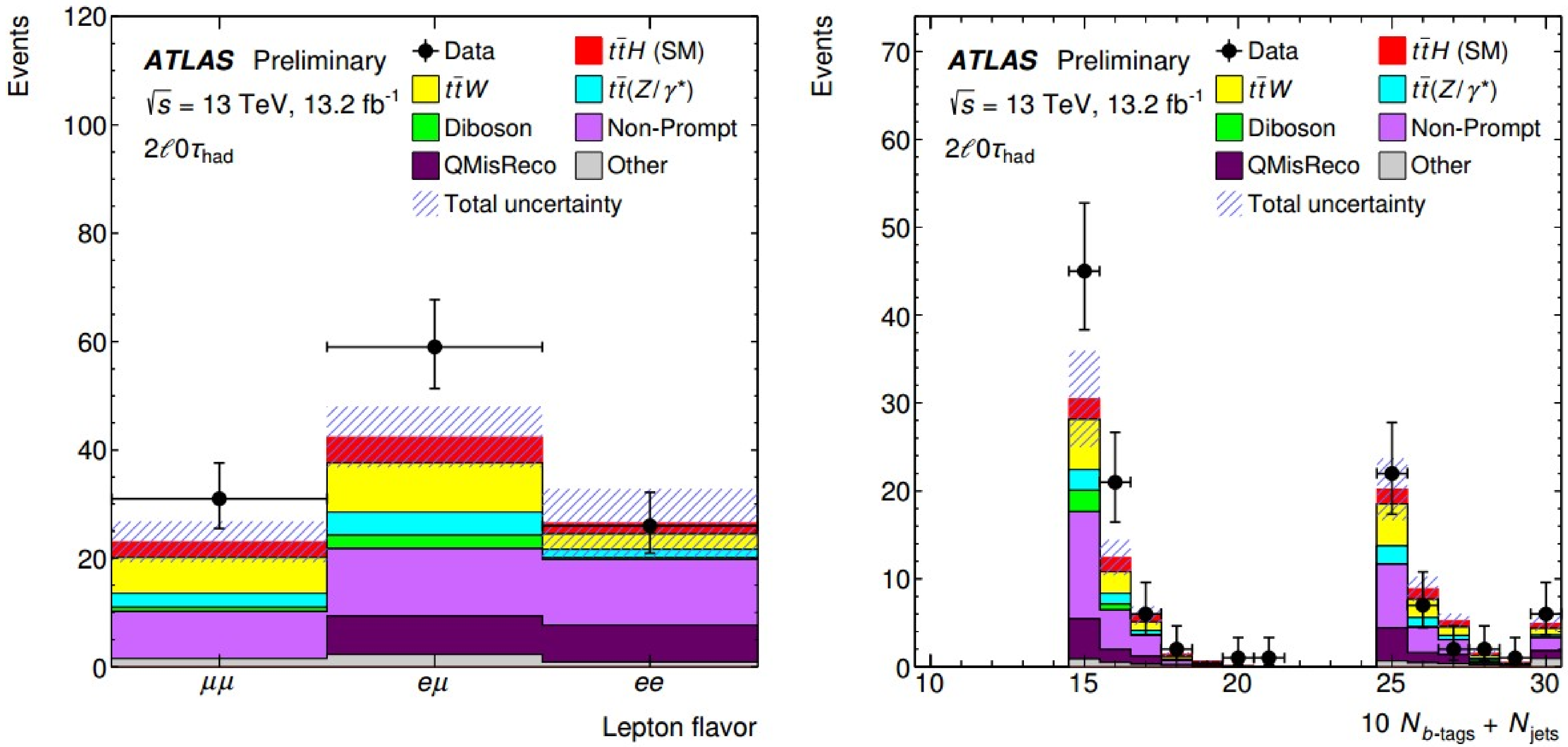
ME gen. PS/UE gen.	Powheg-Box Pythia 6.428	Powheg-Box Herwig++2.7.1	MG5_aMC Herwig++2.7.1	Powheg-Box Pythia 6.428	Powheg-Box Pythia 6.428
Ren. scale	$\sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$\sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$\sqrt{m_t^2 + \frac{1}{2}(p_{\mathrm{T,t}}^2 + p_{\mathrm{T,\bar{t}}}^2)}$	$\frac{1}{2} \cdot \sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$2 \cdot \sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$
Fact. scale	$\sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$\sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$\sqrt{m_t^2 + \frac{1}{2}(p_{\mathrm{T,t}}^2 + p_{\mathrm{T,\bar{t}}}^2)}$	$\frac{1}{2} \cdot \sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$2 \cdot \sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$
hdamp	m_t	m_t	–	$2 \cdot m_t$	m_t
ME PDF	CT10	CT10	CT10	CT10	CT10
PS/UE PDF	CTEQ6L1	CTEQ6L1	CTEQ6L1	CTEQ6L1	CTEQ6L1
Tune	P2012	UE-EE5	UE-EE5	P2012 radHi	P2012 radLo

ME gen. PS/UE gen.	MG5_aMC Herwig++ 2.7.1	MG5_aMC Pythia 8.210	SherpaOL Sherpa
Renorm. scale	μ_{CMMPS}	μ_{CMMPS}	μ_{CMMPS}
Fact. scale	$H_{\mathrm{T}}/2$	$H_{\mathrm{T}}/2$	$H_{\mathrm{T}}/2$
Resumm. scale	$f_{\mathrm{Q}}\sqrt{\hat{s}}$	$f_{\mathrm{Q}}\sqrt{\hat{s}}$	$H_{\mathrm{T}}/2$
ME PDF	NNPDF3.0 4F	NNPDF3.0 4F	CT10 4F
PS/UE PDF	CTEQ6L1	NNPDF2.3	
Tune	UE-EE-5	A14	Author's tune

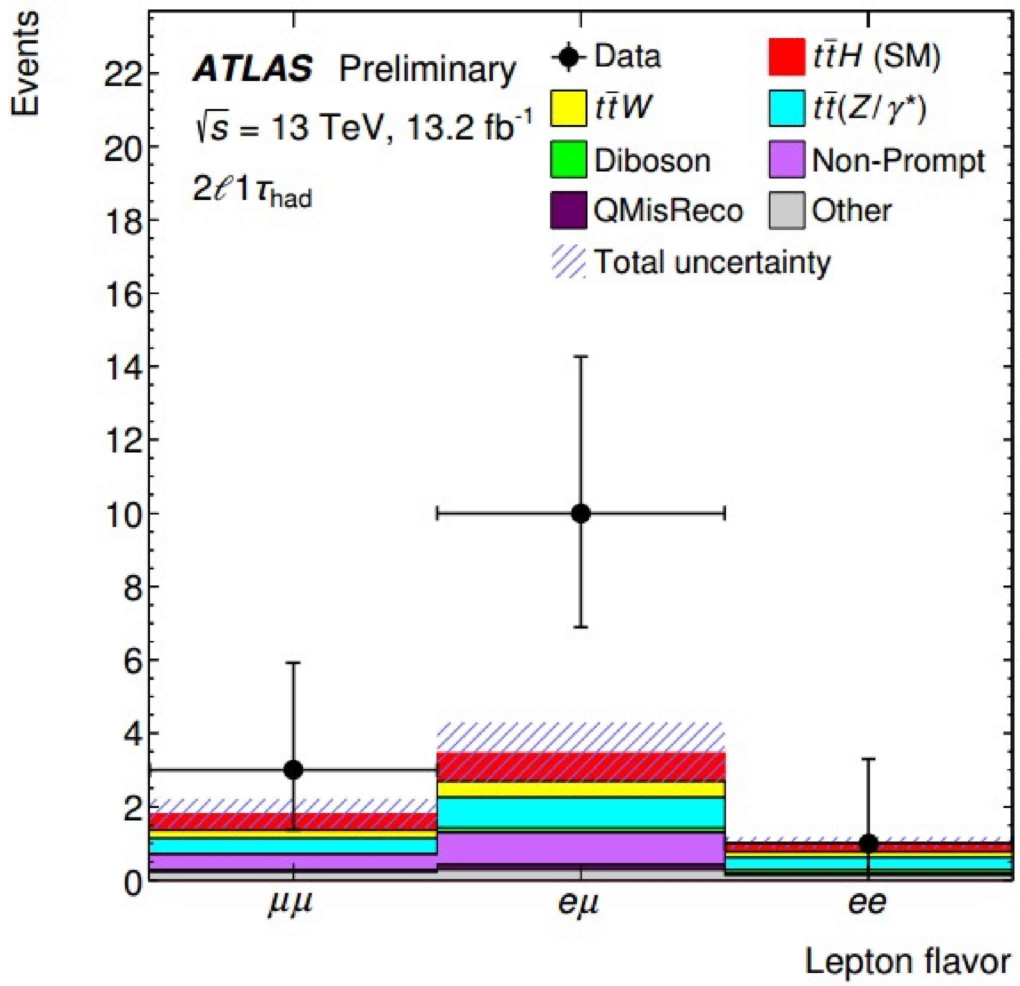
$t\bar{t}H(bb)$ $t\bar{t}$+jets uncertainties

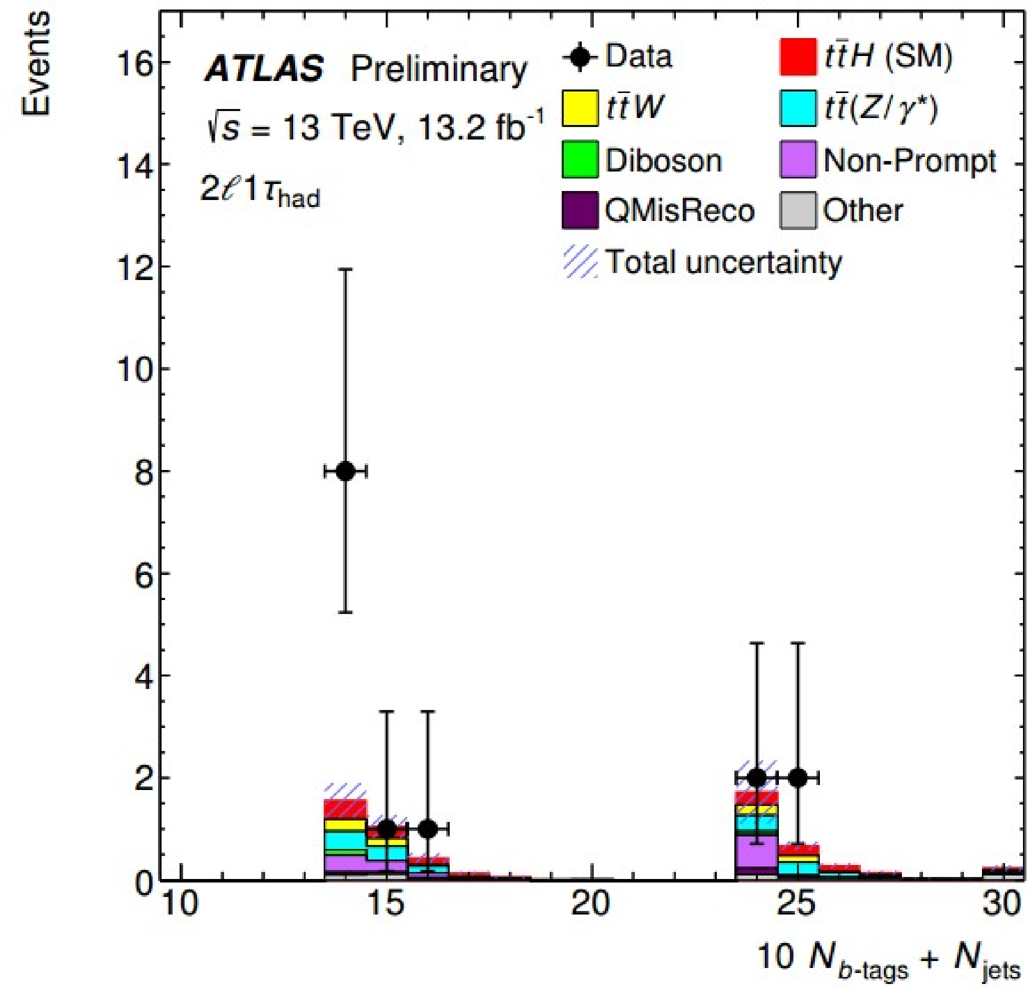
Systematic source	How evaluated	$t\bar{t}$ categories
$t\bar{t}$ cross-section	±6%	All, correlated
NLO generator (*residual*)	Powheg-Box + Herwig++ vs. MG5_aMC + Herwig++	All, uncorrelated
Radiation (*residual*)	Variations of μ_R, μ_F, and *hdamp*	All, uncorrelated
PS & hadronisation (*residual*)	Powheg-Box + Pythia 6 vs. Powheg-Box + Herwig++	All, uncorrelated
NNLO top & $t\bar{t}$ p_T	Maximum variation from any NLO prediction	$t\bar{t}+\geq 1c$, $t\bar{t}$ +light, uncorr.
$t\bar{t}+b\bar{b}$ NLO generator *reweighting*	SherpaOL vs. MG5_aMC+ Pythia8	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PS & hadronis. *reweighting*	MG5_aMC + Pythia8 vs. MG5_aMC + Herwig++	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ renorm. scale *reweighting*	Up or down a by factor of two	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ resumm. scale *reweighting*	Vary μ_Q from $H_T/2$ to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ global scales *reweighting*	Set μ_Q, μ_R, and μ_F to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ shower recoil *reweighting*	Alternative model scheme	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PDF *reweighting*	CT10 vs. MSTW or NNPDF	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ FSR	Radiation variation samples	$t\bar{t}+\geq 1b$
$t\bar{t}+c\bar{c}$ ME calculation	MG5_aMC + Herwig++ inclusive vs. ME prediction	$t\bar{t}+\geq 1c$

$t\bar{t}H$(multilepton) $2\ell0\tau_{had}$ event characteristics

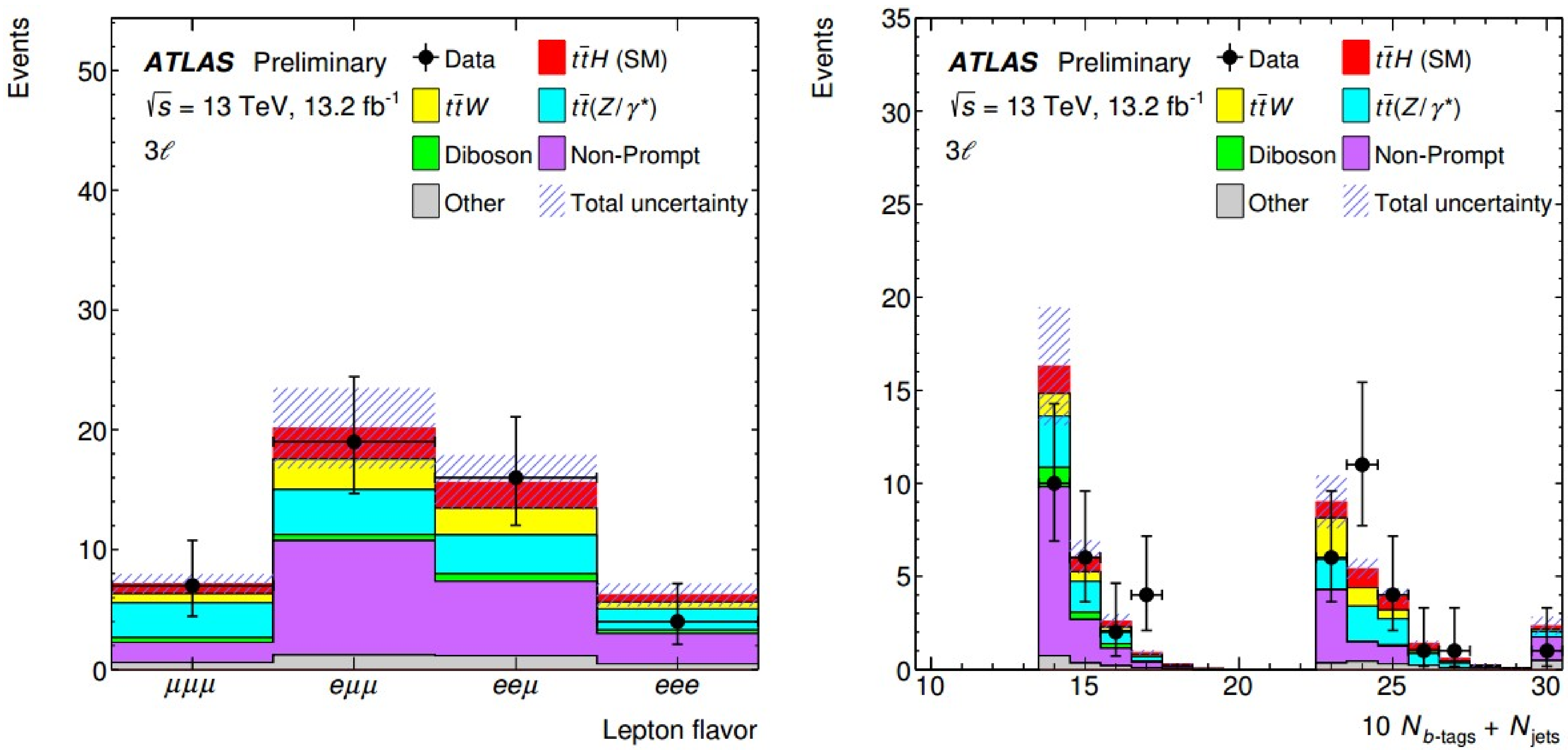


$t\bar{t}H$(multilepton) $2\ell 1\tau_{had}$ event characteristics

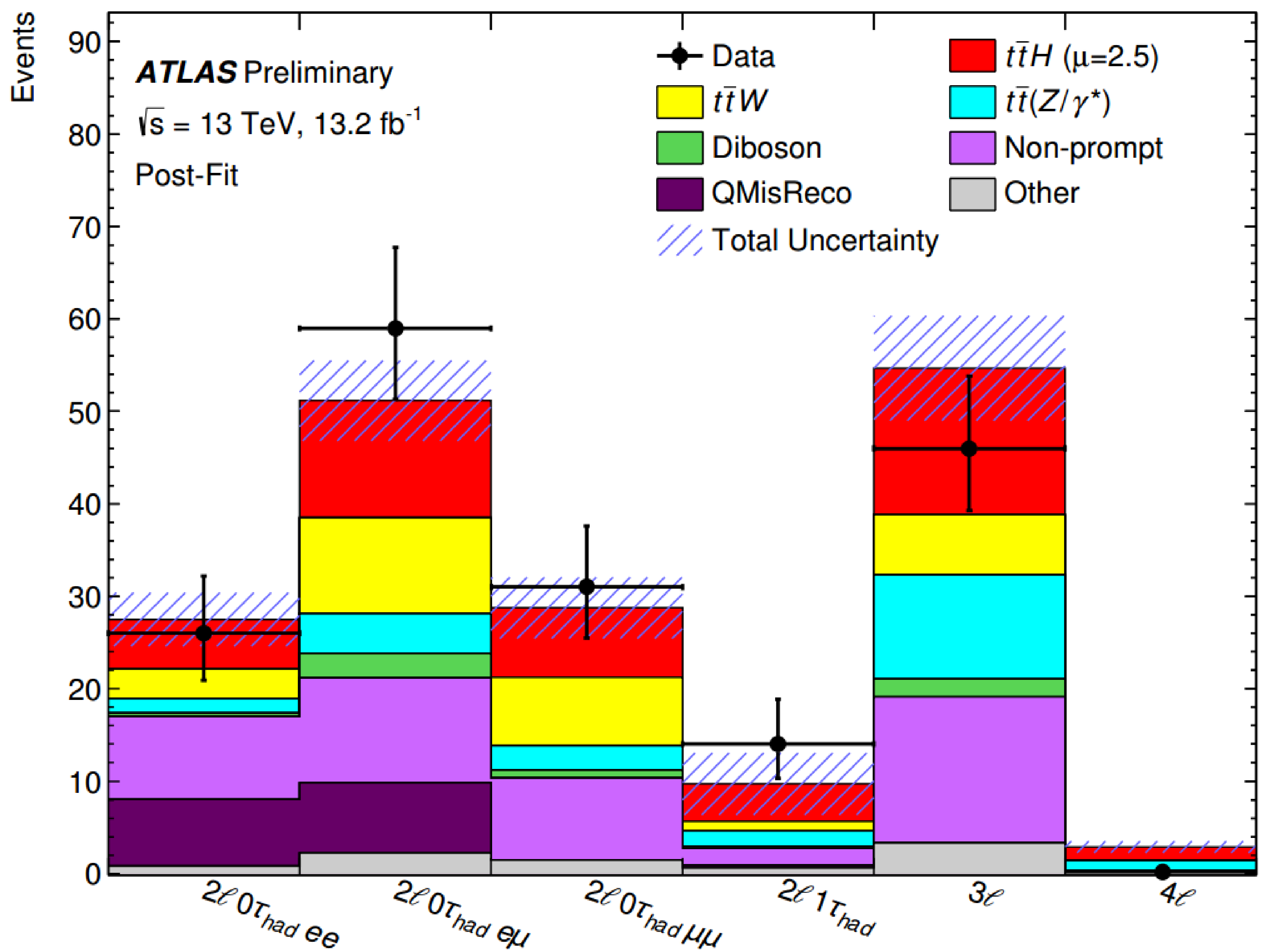




$t\bar{t}H$(multilepton) 3ℓ event characteristics



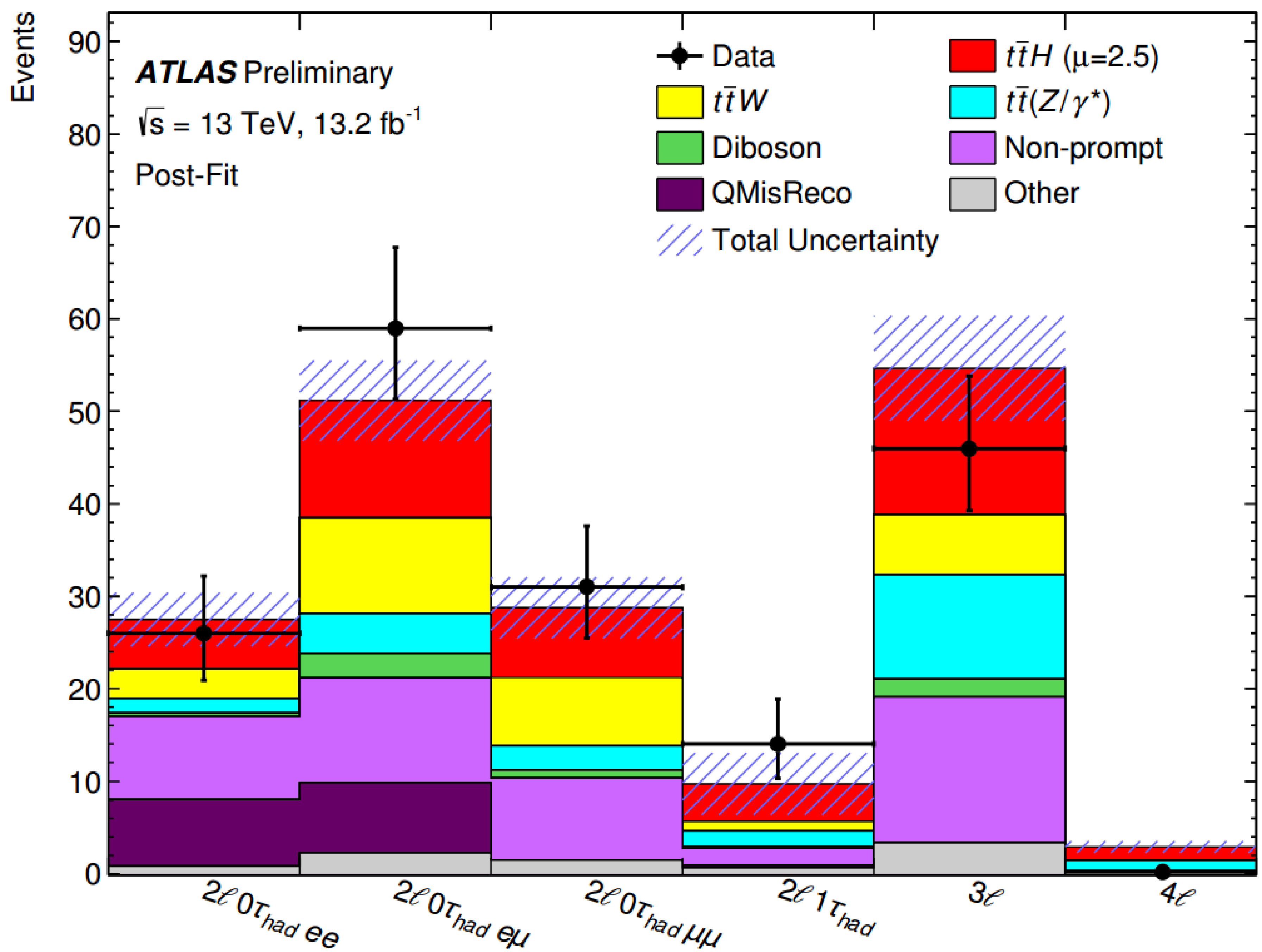
$t\bar{t}$H(multilepton) post-fit yields



$t\bar{t}$H(multilepton) uncertainties

Uncertainty Source	$\Delta\mu$	
Non-prompt leptons and charge misreconstruction	+0.56	−0.64
Jet-vertex association, pileup modeling	+0.48	−0.36
$t\bar{t}W$ modeling	+0.29	−0.31
$t\bar{t}H$ modeling	+0.31	−0.15
Jet energy scale and resolution	+0.22	−0.18
$t\bar{t}Z$ modeling	+0.19	−0.19
Luminosity	+0.19	−0.15
Diboson modeling	+0.15	−0.14
Jet flavor tagging	+0.15	−0.12
Light lepton (e, μ) and τ_{had} ID, isolation, trigger	+0.12	−0.10
Other background modeling	+0.11	−0.11
Total systematic uncertainty	+1.1	−0.9

$t\bar{t}$H(multilepton) post-fit yields



$t\bar{t}H$(multilepton) 3ℓ event characteristics