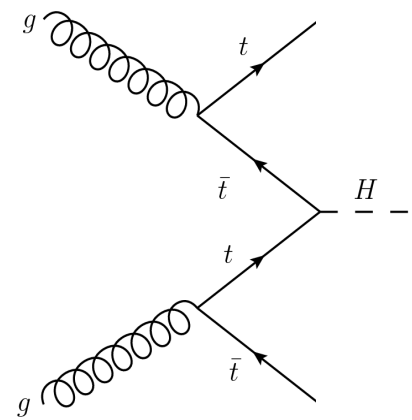
ATLAS results on ttH

Margherita Spalla (*)
on behalf of the ATLAS Collaboration

(*) Max Planck Institut für Physik, München

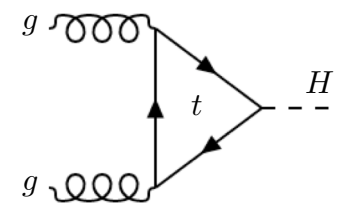
ttH production channel

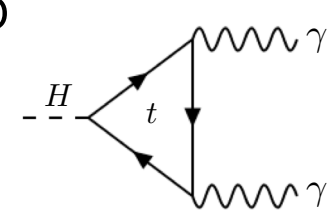
- Direct test of top-Higgs coupling
  - of particular interest, as *t* is the heaviest SM particle



- top-Higgs coupling could be very sensitive to physics beyond the Standard Model (BSM)

- Indirect measurements from combined fit to multiple H measurements
  - assume no BSM contribution to the loop



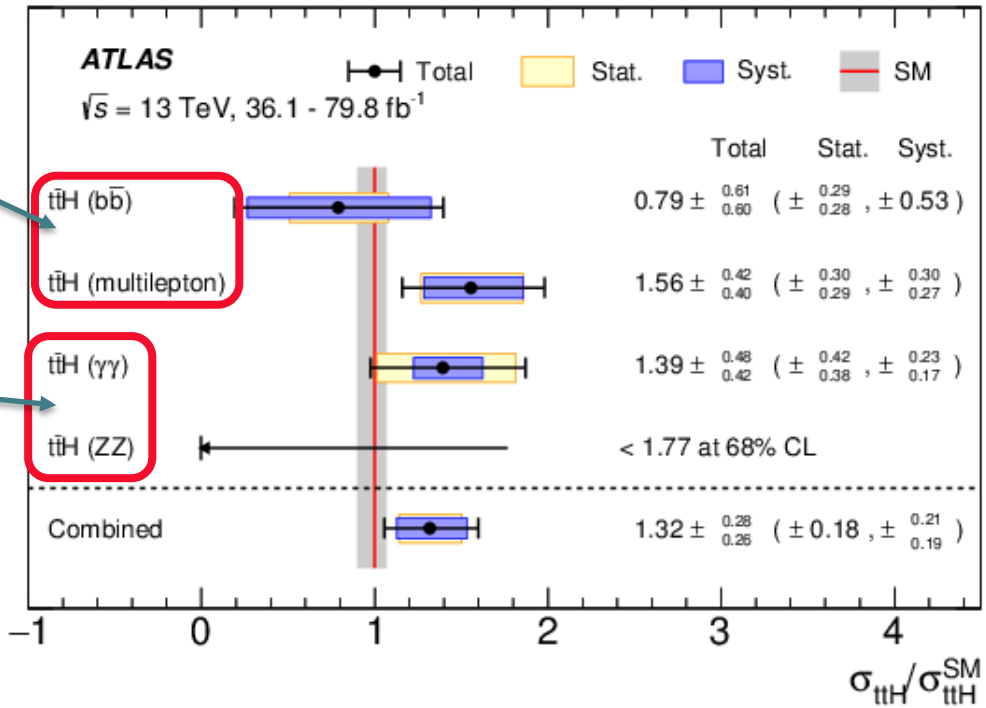


ttH observation by ATLAS

- ATLAS ttH observation paper came in 2018
  - From combination of analysis in multiple decay channels
    - » Phys. Lett. B 784 (2018) 173 (more details later on)

36.1 fb^{-1}

79.8 fb^{-1}
» update with full run 2 (139 fb^{-1}) in 2019



$ttH(H \rightarrow \gamma\gamma)$

L_{int} = 139 fb^{-1} (ATLAS-CONF-2019-004)

L_{int} = 79.8 fb^{-1} (Phys. Lett. B 784 (2018) 173)

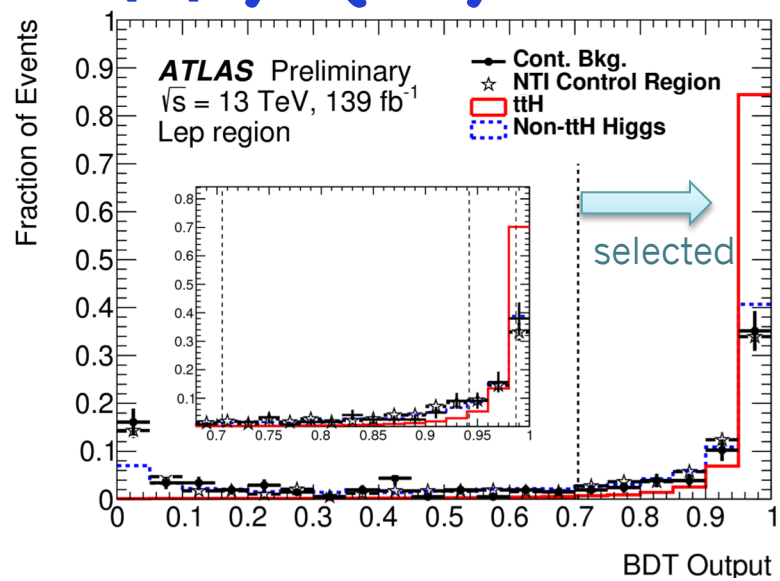
- Clean final state
- Very similar analysis strategy for 79.8 fb^{-1} and full Run 2 analysis
- Event reconstruction:
  - Higgs: 2 well reconstructed, isolated γ, $M_{\gamma\gamma}$ between 105 and 160 GeV
  - All tt decays considered
    - Two signal regions for (semi)leptonic ('Lep') and hadronic ('Had') events

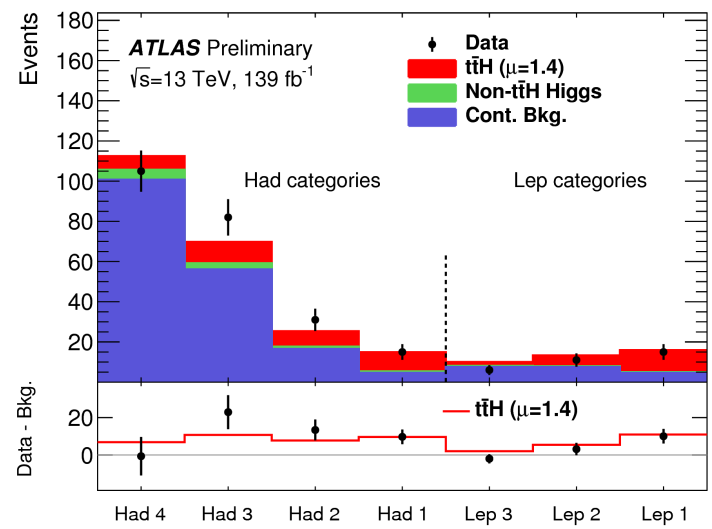
Plots from: ATLAS-CONF-2019-004

ttH(H→γγ) (2)

L_{int} = 139 fb^{-1}
L_{int} = 79.8 fb^{-1}

- Additional selection via Boosted Decision Trees (BDT)
  - One per signal region
  - Inputs: γ, jet and lepton kinematics, E_T^{miss}(✯), b-tagging
- Minimum BDT score required.
  - Selected events divided in BDT bins
  - Chosen to optimize expected ttH sensitivity
- Signal and background modeled with analytical functions in each category



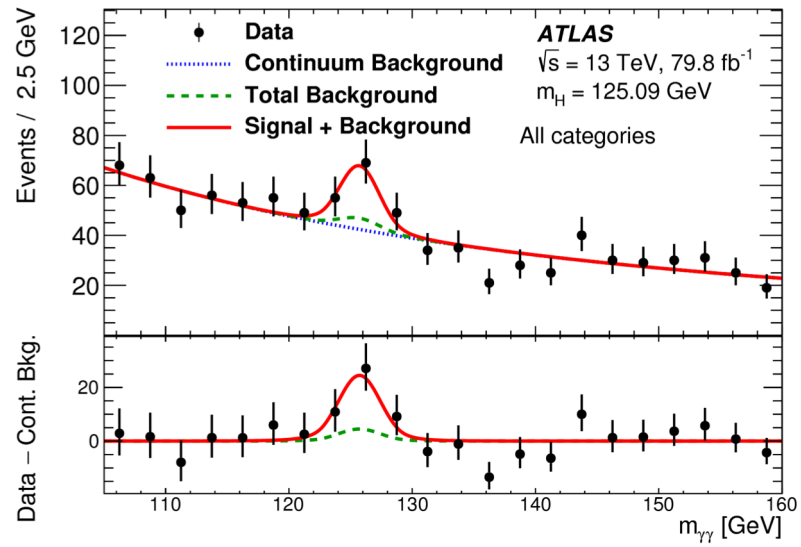


(✯) E_T^{miss} = missing transverse momentum

From: Phys. Lett. B 784 (2018) 173

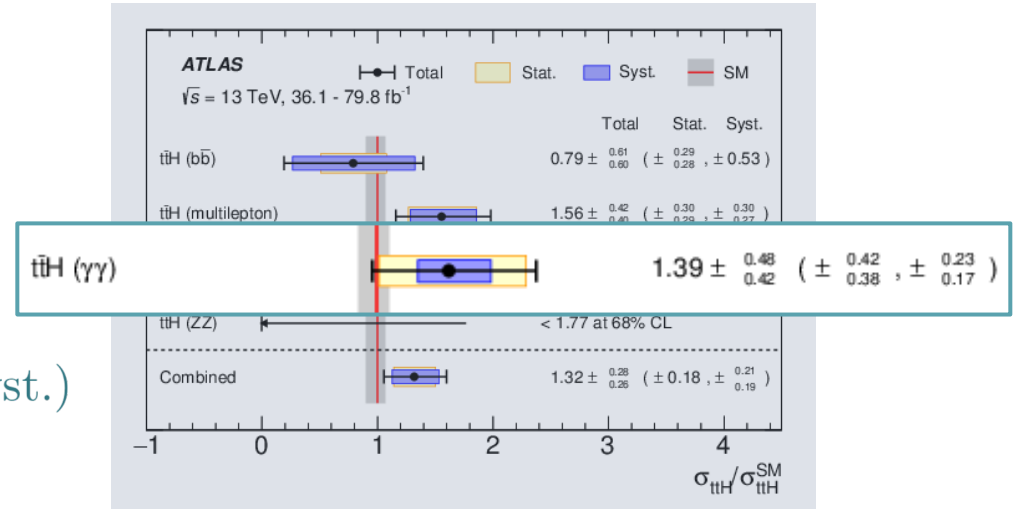
ttH(H→γγ): 79.8 fb^{-1} results

- Maximum Likelihood fit to $\gamma\gamma$ invariant mass spectrum in each category
  - H mass constrained
- Observed significance: 4.1 σ
  - Expected: 3.7 σ



$$\sigma_{\mathrm{ttH}} = 710\ ^{+210}_{-190}(\mathrm{stat.})\ ^{+120}_{-90}(\mathrm{syst.})\ \mathrm{fb}$$

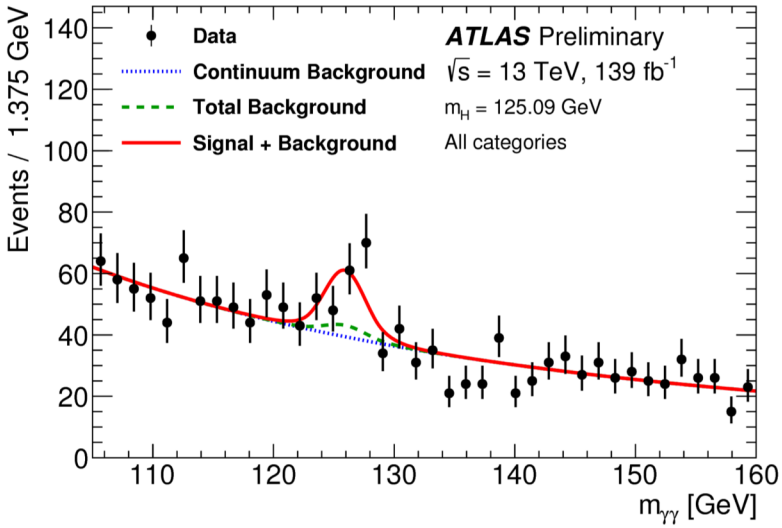
$$\frac{\sigma_{\mathrm{ttH}}}{\sigma_{\mathrm{ttH}}^{\mathrm{SM}}} = 1.39\ \pm^{0.42}_{0.38}\ (\mathrm{Stat.})\ \pm^{0.23}_{0.17}\ (\mathrm{Syst.})$$



From: ATLAS-CONF-2019-004

ttH(H→γγ): 139 fb^{-1} results

- Maximum Likelihood fit on all categories
  - H mass constrained to experimental value
- ttH observed with 4.9 σ significance
  - Expected: 4.2 σ
- Remains statistically dominated
- Measured cross section still ~1.4 times the Standard Model expectation
  - Remains compatible given the uncertainties



same size

$$\sigma_{\mathrm{ttH}} \times B_{\gamma\gamma} = 1.59\ ^{+0.38}_{-0.36}(\mathrm{stat.})\ ^{+0.15}_{-0.12}(\mathrm{exp.})\ ^{+0.15}_{-0.11}(\mathrm{theo.})\ \mathrm{fb}$$

Prediction:

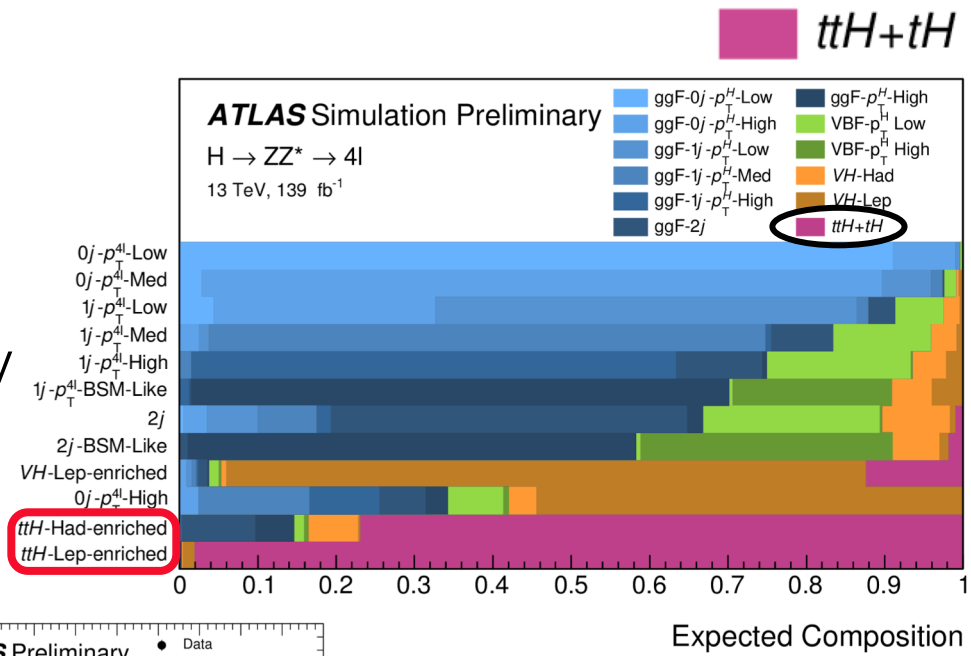
$$\sigma_{\mathrm{ttH}} \times B_{\gamma\gamma}\ (\mathrm{SM}) = 1.15\ ^{+0.09}_{-0.12}\ \mathrm{fb}$$

$$\frac{\sigma_{\mathrm{ttH}}}{\sigma_{\mathrm{ttH}}^{\mathrm{SM}}} = 1.38\ \pm^{0.33}_{0.31}\ (\mathrm{Stat.})\ \pm^{0.13}_{0.11}\ (\mathrm{exp.})\ \pm^{0.22}_{0.14}\ (\mathrm{theo.})$$

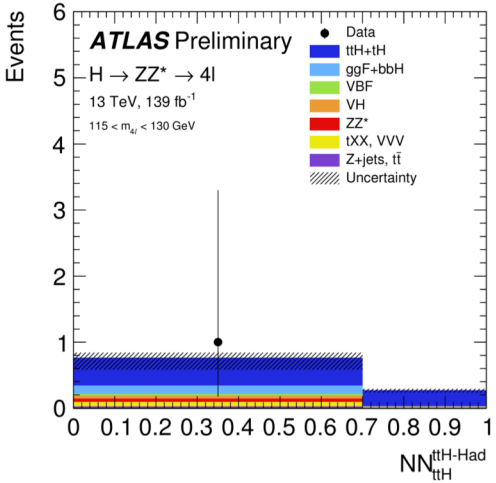
L_{int} = 139 fb^{-1} (ATLAS-CONF-2019-025)

ttH(H→ZZ*→4ℓ)

- Two opposite-charge, same-flavor lepton pairs in the Higgs mass window
- Two categories for ttH production mode
  - 'Lep': at least one leptonically decaying W (from t)
  - 'Had': fully hadronic tt decay
  - More categories as part of larger H→ZZ*→4ℓ analysis



- Further NN selection on 'Had' category
  - Combination of multiple NN in a final discriminant



- 79.8 fb^{-1}: similar strategy but only focusing on ttH
- No events were observed

L_{int} = 79.8 fb^{-1} (Phys. Lett. B 784 (2018) 173)

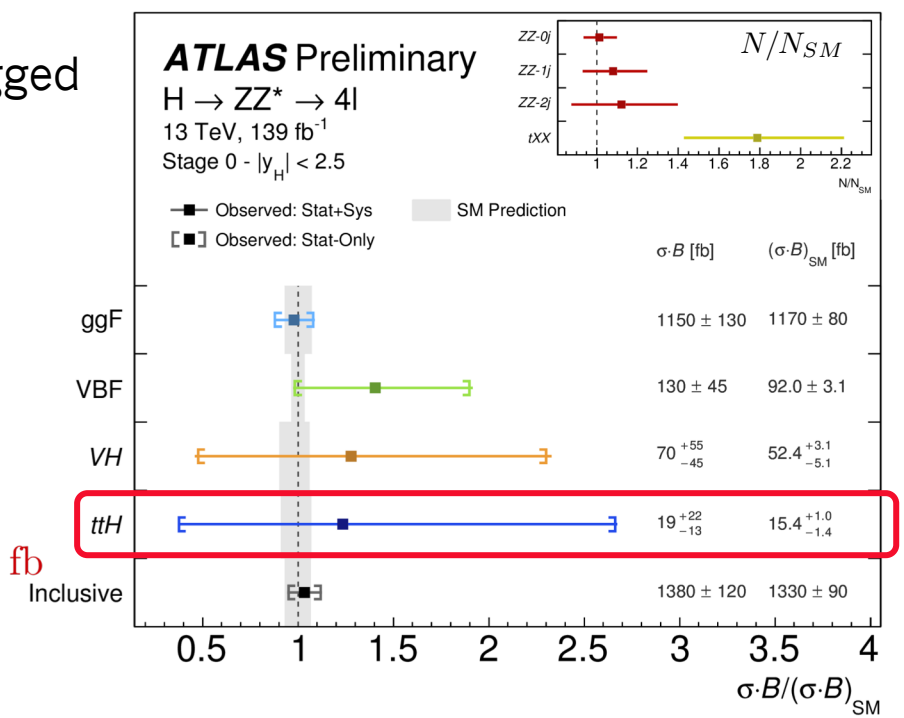
From: ATLAS-CONF-2019-025

ttH(H→ZZ*→4ℓ): 139 fb^{-1} results

- Global likelihood fit on NN output
  - » Event yield used for (semi)leptonic ttH
- ttZ/ttW/tWZ background constrained from control region
  - similar selection to ttH
    - » cut on number of jets and b-tagged jets
  - missing transverse momentum
  - $M_{4\ell}$ sidebands
- No disagreement with SM
  - Statistics is however too low for conclusions

Reconstructed event category	Total expected events	Observed events
ttH-Had-enriched	1.32 ± 0.17	1
ttH-Lep-enriched	0.42 ± 0.04	1

tXX = ttZ/ttW/tWZ



$$\sigma_{\mathrm{ttH}} \times B_{ZZ^* \to 4\ell} = 19\ ^{+22}_{-13}(\mathrm{stat.})\ \pm 2(\mathrm{exp.})\ \pm 2(\mathrm{theo.})\ \mathrm{fb}$$

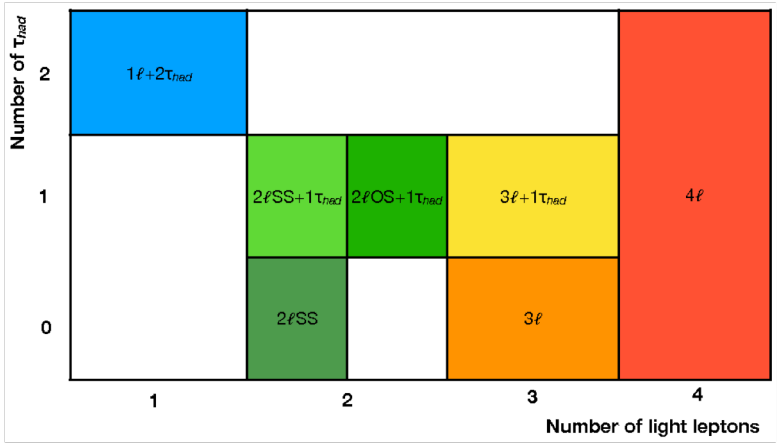
$$\sigma_{\mathrm{ttH}} \times B_{ZZ^* \to 4\ell}\ (\mathrm{SM}) = 15.4\ ^{+1.0}_{-1.4}\ \mathrm{fb}$$

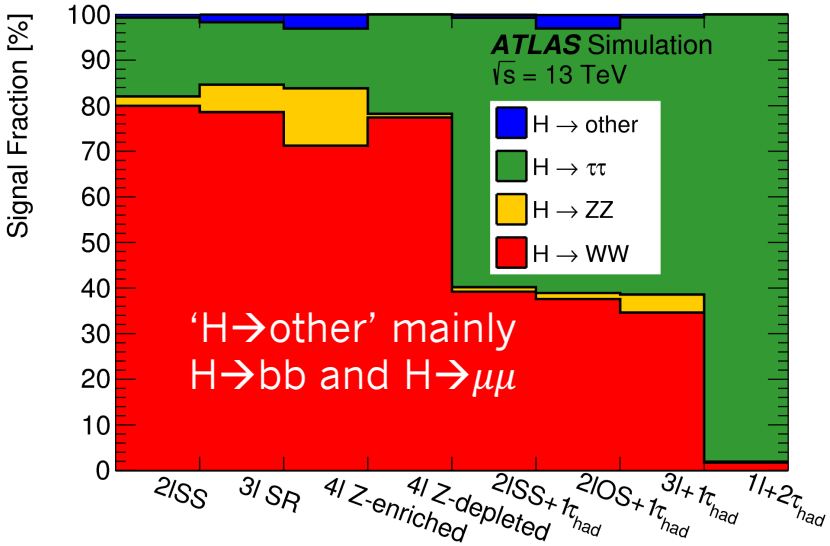
From: Phys. Rev. D 97, 072003

$L_{int} = 36.1\ fb^{-1}$

ttH (H to multilepton)

- 7 final states:
  - H decaying to light leptons (e or μ) or hadronically decaying τ
  - Sensitive to multiple ttH decay modes:
    - » H→$\tau\tau$
    - » H→WW*
    - » H→ZZ*→$\ell\ell\nu\nu/\ell\ell qq$
- Built to be orthogonal to
    - » H→ ZZ*→4ℓ,
    - » H→ bb,
    - » H→ $\gamma\gamma$
  - Overlap found to be negligible



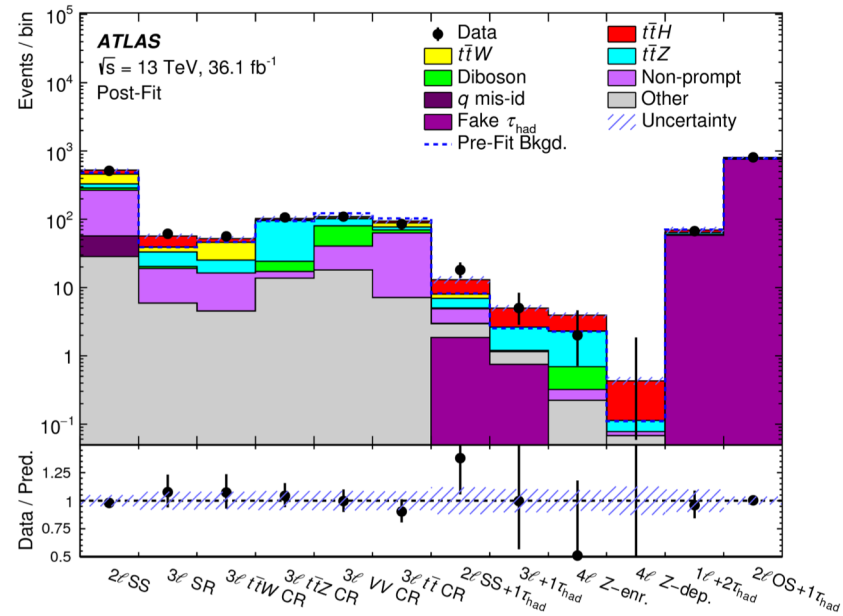


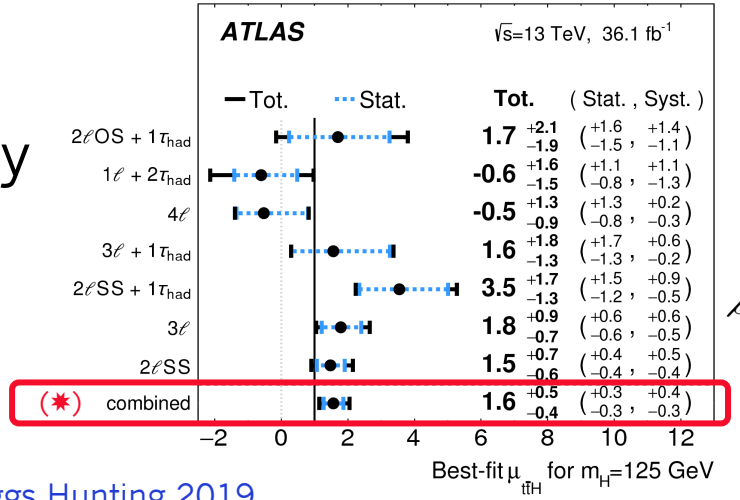
From: Phys. Rev. D 97, 072003

$L_{int} = 36.1\ fb^{-1}$

ttH (H to multilepton) (2)

- Additional event selection on each final state
  - BDTs used for most of them
- Combined likelihood fit on all final states (✱)
- Significance: 4.1σ
  - Expected: 2.8 σ
- Signal modelling uncertainty has the largest impact





$\mu_{t\bar{t}H}$ is $\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}^{SM}$ (fit parameter)

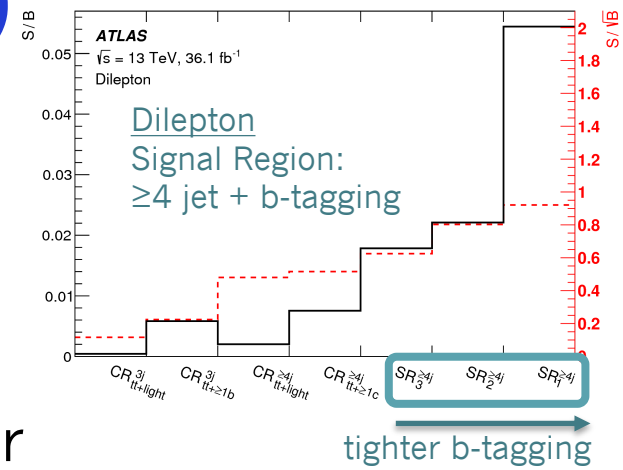
$$\sigma_{\mathrm{ttH}} = 790 \ \pm \ 150(\mathrm{stat.})\ ^{+170}_{-150}(\mathrm{syst.})\ \mathrm{fb}$$

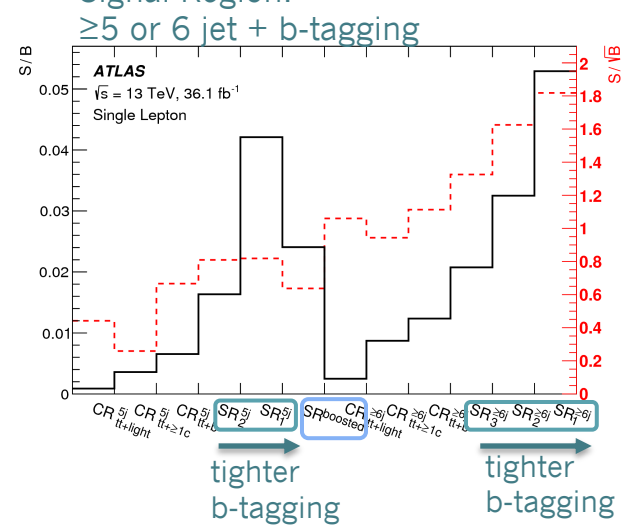
From: Phys. Rev. D 97, 072016

$L_{int} = 36.1\ fb^{-1}$

ttH (H→bb)

- One or two leptons from tt decay
  - Single lepton channel: a boosted final state is also considered
- Further categorized according to number of jets and jets' b-tagging score
  - no categories for the boosted
- BDT to disentangle ttH
  - Each category treated separately
  - Combines intermediate multivariate techniques to improve signal separation



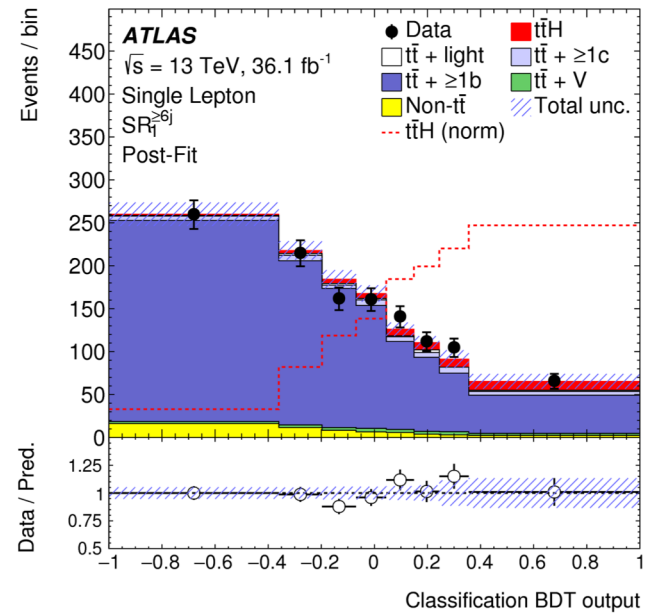


From: Phys. Rev. D 97, 072016

$L_{int} = 36.1\ fb^{-1}$

ttH (H→bb) (2)

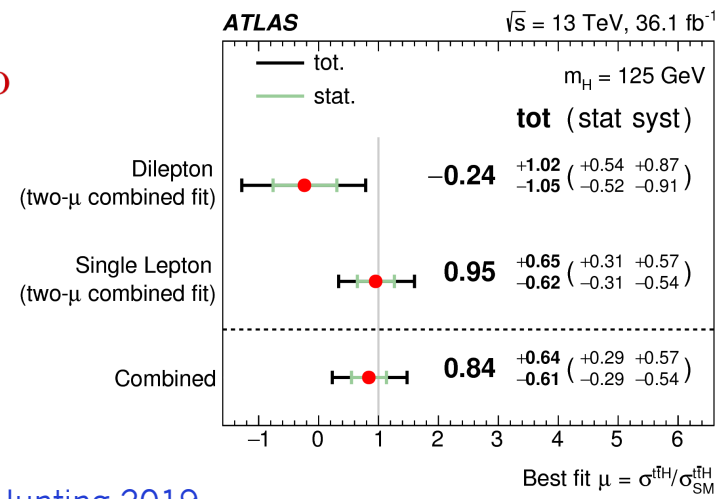
- Global likelihood fit on all categories
- BDT output is the fit variable
  - fit variable for control region: overall event yield or scalar sum jets p_T



- Results compatible with SM
  - Significance: 1.4 σ
    - Expected: 1.6 σ

$$\sigma_{\mathrm{ttH}} = 400\ ^{+150}_{-140}(\mathrm{stat.})\ \pm\ 270(\mathrm{syst.})\ \mathrm{fb}$$

- Largest uncertainty:
  - modeling of tt + heavy flavor background



Back to combination

- 13 TeV cross-section from combined fit
  - $\gamma\gamma$ (79.8 fb^{-1}), ZZ*(4ℓ) (79.8 fb^{-1}), bb (36.1 fb^{-1}), multilepton (36.1 fb^{-1})
  - significance 5.8 σ
    - » expected 4.9 σ
  - uncertainty: large contribution from modelling
    - » tt + heavy flavor

Uncertainty source	$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ [%]
Theory uncertainties (modelling)	11.9
$t\bar{t}$ + heavy flavour	9.9
$t\bar{t}H$	6.0
Non-$t\bar{t}H$ Higgs boson production modes	1.5
Other background processes	2.2
Experimental uncertainties	9.3
Fake leptons	5.2
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	4.9
Electrons, photons	3.2
Luminosity	3.0
τ-lepton	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4

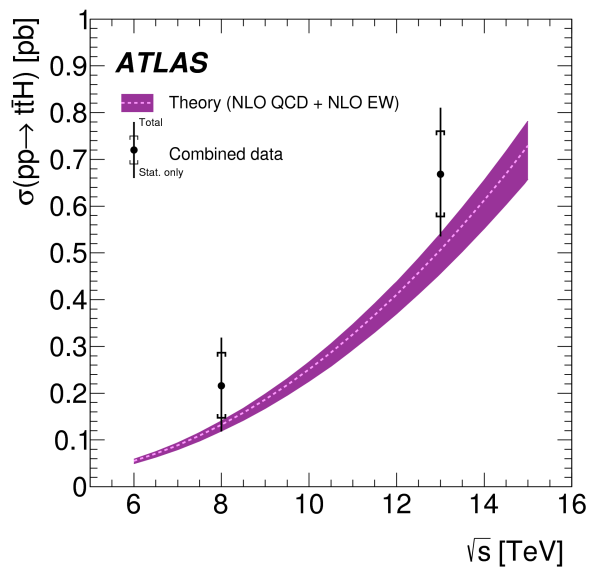
uncertainties on 13 TeV cross section

- Further combination with 8 TeV results
  - Significance raises to 6.3σ (5.1σ expected)

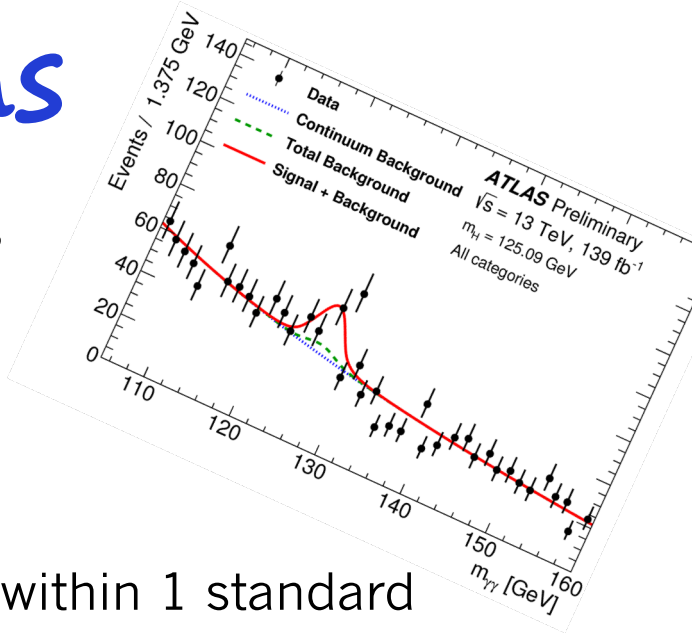
- Measured cross section about 1σ over NLO prediction

$$\sigma_{\mathrm{ttH}} = 670 \pm 90(\mathrm{stat.})\ ^{+110}_{-100}(\mathrm{syst.})\ \mathrm{fb}$$

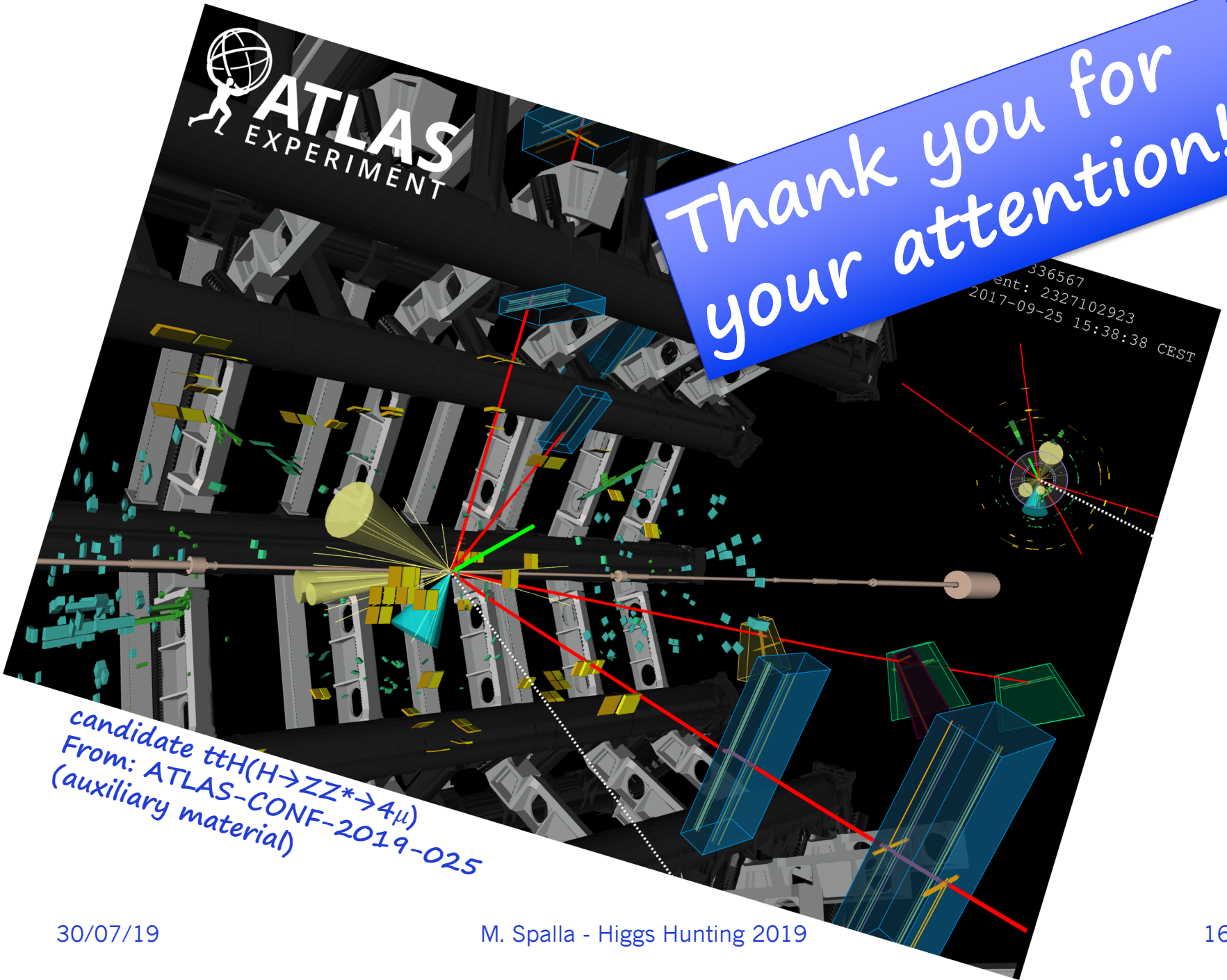
$$\sigma_{\mathrm{ttH}}\ (\mathrm{SM}) = 507\ ^{+35}_{-50}\ \mathrm{fb}$$ (NLO QCD + NLO EW)



Conclusions



- ttH associated production observed in 2018
  - From combination of multiple channels
- Full run 2 measurement in H→$\gamma\gamma$ channel reaches 4.9σ
- Measured cross section agrees with the SM within 1 standard deviation
  - prediction at NLO (both QCD and electroweak)
- Modeling uncertainties contribute significantly to the total systematics
- Entire run 2 dataset yet to be fully exploited
- ATLAS effort on ttH not over: stay tuned for more!



Thank you for your attention!

candidate ttH(H→ZZ*→4μ)
From: ATLAS-CONF-2019-025
(auxiliary material)

BACKUP

Uncertainties in ttH(H→γγ) cross section fit

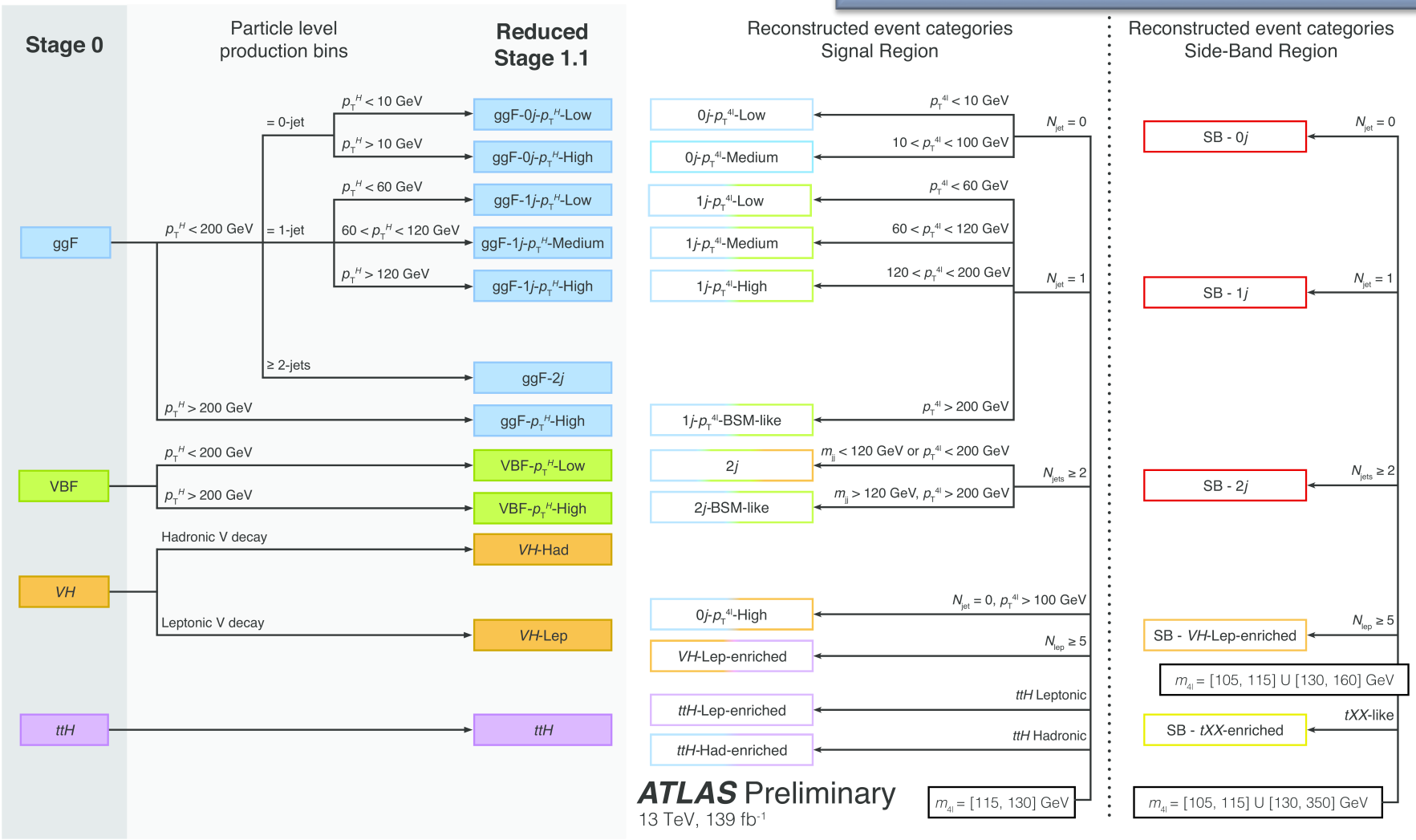
L_{int} = 139 fb^{-1}
(ATLAS-CONF-2019-004)

Uncertainty source	$\Delta\sigma_{\text{low}}/\sigma$ [%]	$\Delta\sigma_{\text{high}}/\sigma$ [%]
Theory uncertainties	6.6	9.7
Underlying Event and Parton Shower (UEPS)	5.0	7.2
Modeling of Heavy Flavor Jets in non-$t\bar{t}H$ Processes	4.0	3.4
Higher-Order QCD Terms (QCD)	3.3	4.7
Parton Distribution Function and α_S Scale (PDF+α_S)	0.3	0.5
Non-$t\bar{t}H$ Cross Section and Branching Ratio to $\gamma\gamma$ (BR)	0.4	0.3
Experimental uncertainties	7.8	9.1
Photon Energy Resolution (PER)	5.5	6.2
Photon Energy Scale (PES)	2.8	2.7
Jet/$E_{\text{T}}^{\text{miss}}$	2.3	2.7
Photon Efficiency	1.9	2.7
Background Modeling	2.1	2.0
Flavor Tagging	0.9	1.1
Leptons	0.4	0.6
Pileup	1.0	1.5
Luminosity and Trigger	1.6	2.3
Higgs Boson Mass	1.6	1.5

From: ATLAS-CONF-2019-025

ttH(H→ZZ*→4ℓ) with 139 fb^{-1}: category definition

- **ttH leptonic**: at least 1 lepton + minimum number of jets and b-jets
- **ttH hadronic**: minimum number of jets and b-jets (no leptons)
- **tXX**: minimum number of jets and b-jets + MET + sideband



From: ATLAS-CONF-2019-025

ttH(H→ZZ*→4ℓ) with 139 fb^{-1}: systematic uncertainty

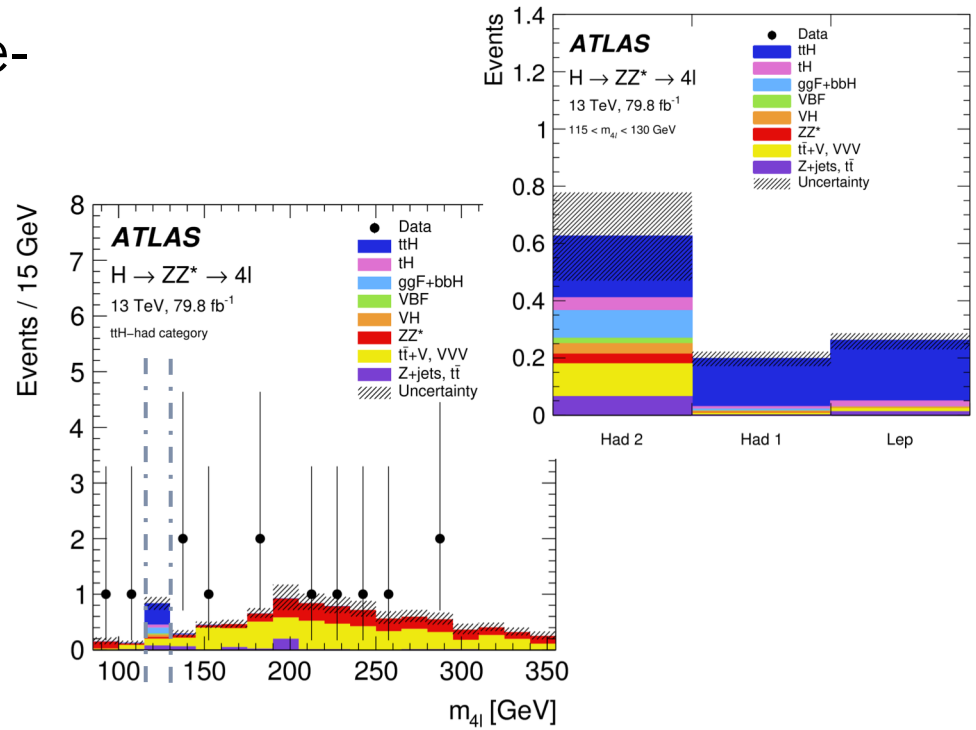
Measurement	Experimental uncertainties [%]				Theory uncertainties [%]					
	Lum.	e, μ, pile-up	Jets, flavour tagging	Reducible backgr.	ZZ^* backgr	tXX backgr.	Signal PDF	Signal QCD scale	Signal Parton Shower	Signal Composition
Fiducial cross section										
σ_{comb}	1.7	2.5	–	< 0.5	1	< 0.5	< 0.5	2	1	< 0.5
Per decay final state fiducial cross sections										
4μ	1.7	2.5	–	0.5	1	< 0.5	< 0.5	2	1	< 0.5
$4e$	1.7	7	–	0.5	1.5	< 0.5	< 0.5	2	0.5	< 0.5
$2\mu 2e$	1.7	5.5	–	0.5	1	< 0.5	< 0.5	2	1.5	< 0.5
$2e2\mu$	1.7	2.0	–	0.5	1	< 0.5	< 0.5	2	1	< 0.5
Stage-0 production bin cross sections										
ggF	1.7	1.5	1	0.5	1.5	< 0.5	0.5	1	2	–
VBF	1.7	1	4.5	0.5	2	0.5	1.5	8	6	–
VH	1.8	1.5	3.5	1	5	0.5	2	12	8	–
ttH	1.7	1	4.5	1	1	0.5	0.5	8	4	–

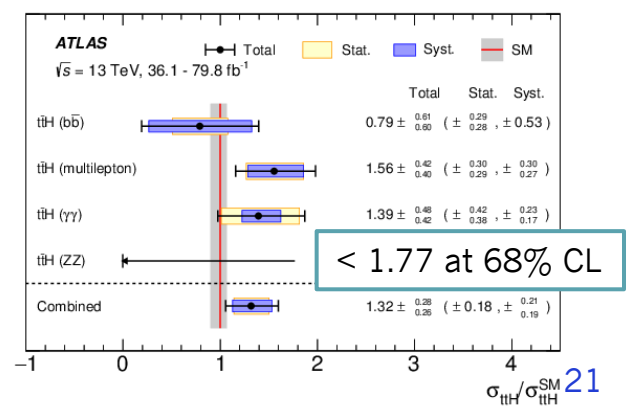
From: Phys. Lett. B 784 (2018) 173

ttH(H→ZZ*→4ℓ) : 79.8 fb^{-1}

- Two opposite-charge, same-flavor lepton pairs in the Higgs mass window
- Two categories for tt decay
  - 'Lep': at least one leptonically decaying W
  - 'Had': fully hadronic
- Further BDT selection on 'Had' category
  - split in two BDT bins
- No events observed
  - Expected significance: 1.2σ

$$\sigma_{\mathrm{ttH}} < 900 \text{ fb } (68\% \text{ CL})$$





Uncertainties breakdown in ttH(H→multilepton) fit

From: Phys. Rev. D 97, 072003

Uncertainty Source	$\Delta\mu$	
$t\bar{t}H$ modeling (cross section)	+0.20	−0.09
Jet energy scale and resolution	+0.18	−0.15
Non-prompt light-lepton estimates	+0.15	−0.13
Jet flavor tagging and τ_{had} identification	+0.11	−0.09
$t\bar{t}W$ modeling	+0.10	−0.09
$t\bar{t}Z$ modeling	+0.08	−0.07
Other background modeling	+0.08	−0.07
Luminosity	+0.08	−0.06
$t\bar{t}H$ modeling (acceptance)	+0.08	−0.04
Fake τ_{had} estimates	+0.07	−0.07
Other experimental uncertainties	+0.05	−0.04
Simulation sample size	+0.04	−0.04
Charge misassignment	+0.01	−0.01
Total systematic uncertainty	+0.39	−0.30

$$\mu = \sigma_{ttH}/\sigma_{ttH}^{SM}$$

Uncertainties breakdown in ttH(H→bb) fit

From: Phys. Rev. D 97, 072016

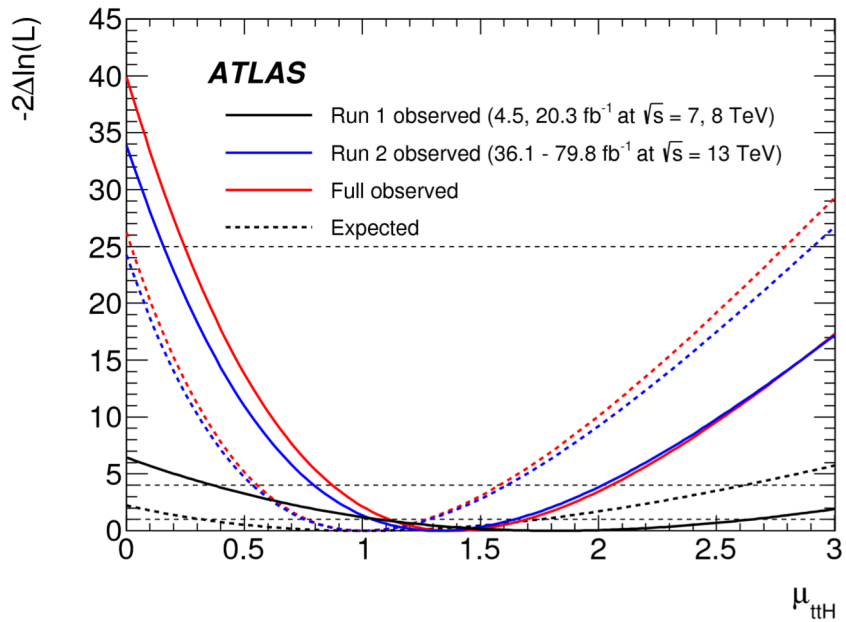
Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modeling	+0.46	−0.46
Background-model stat. unc.	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modeling	+0.22	−0.05
$t\bar{t} + \geq 1c$ modeling	+0.09	−0.11
JVT, pileup modeling	+0.03	−0.05
Other background modeling	+0.08	−0.08
$t\bar{t}$ + light modeling	+0.06	−0.03
Luminosity	+0.03	−0.02
Light lepton (e, μ) id., isolation, trigger	+0.03	−0.04
Total systematic uncertainty	+0.57	−0.54
$t\bar{t} + \geq 1b$ normalization	+0.09	−0.10
$t\bar{t} + \geq 1c$ normalization	+0.02	−0.03
Intrinsic statistical uncertainty	+0.21	−0.20
Total statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61

$$\mu = \sigma_{ttH}/\sigma_{ttH}^{SM}$$

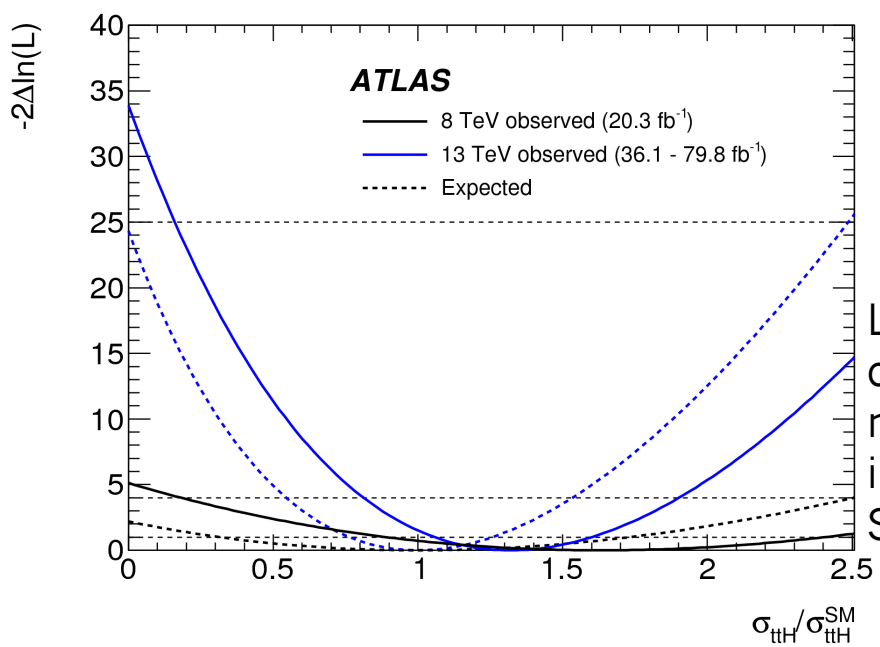
Combination fit

From combination paper auxiliary material:
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2018-13

Likelihood curve of the ttH signal-strength combination, including the systematic uncertainties in the SM prediction in the fit.



Signal-strength: $\mu_{ttH} = \sigma_{ttH}/\sigma_{ttH}^{SM}$



Likelihood curve of the ttH cross-section combination. The measured cross section is normalized to the SM prediction, without including the systematic uncertainties in the SM prediction in the fit.

Summary of cross sections from combination paper

Plots from: Phys. Lett. B 784 (2018) 173

Analysis	Integrated luminosity [fb^{-1}]	$t\bar{t}H$ cross section [fb]	Obs. sign.	Exp. sign.
$H \to \gamma\gamma$	79.8	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)	4.1 σ	3.7 σ
$H \to$ multilepton	36.1	790 $\pm$150 (stat.) $^{+150}_{-140}$ (syst.)	4.1 σ	2.8 σ
$H \to b\bar{b}$	36.1	400 $^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)	1.4 σ	1.6 σ
$H \to ZZ^* \to 4\ell$	79.8	<900 (68% CL)	0 σ	1.2 σ
Combined (13 TeV)	36.1–79.8	670 $\pm$ 90 (stat.) $^{+110}_{-100}$ (syst.)	5.8 σ	4.9 σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	–	6.3 σ	5.1 σ