27th Workshop on Deep-Inelastic Scattering and Related Subjects – DIS2019
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Higgs boson production in association with a ttbar pair at the ATLAS experiment

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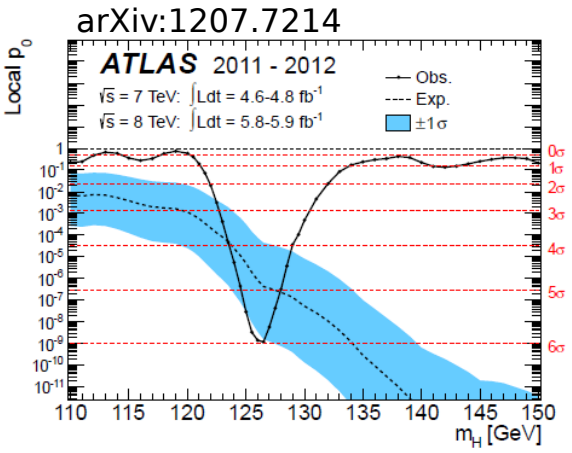
On behalf of the ATLAS Collaboration

Introduction and Motivation

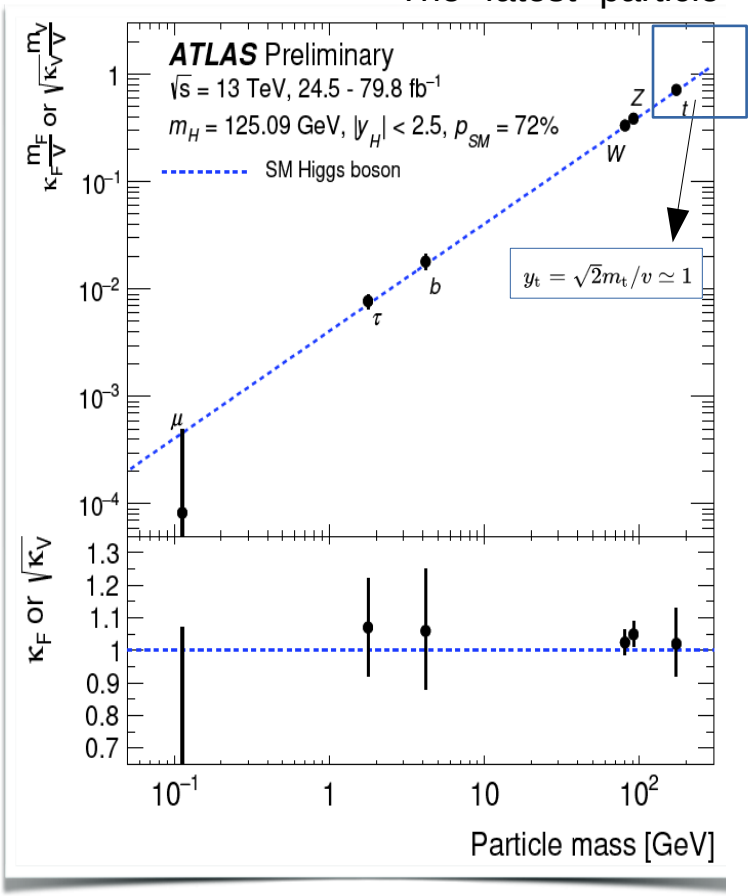
The “fatest” particle



Discovery of the Higgs (125 GeV) by ATLAS and CMS collaboration

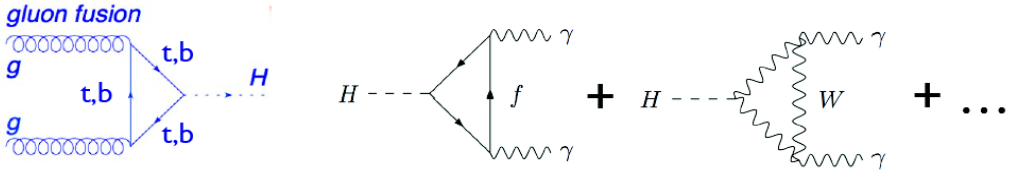
- great success of particle physics, especially Standard Model (SM)

All measurements compatible with SM predictions.



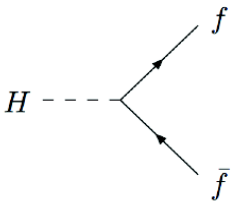
- **Top quark Yukawa coupling:**
  - **Fundamental parameter of the SM, ttH production cross-section controlled by the top Yukawa coupling.**
  - **Production and decay signatures sensitive to new physics**

Indirect probe *(through loop diagrams)*



$gg \to H$ $\qquad$ $H \to \gamma\gamma$

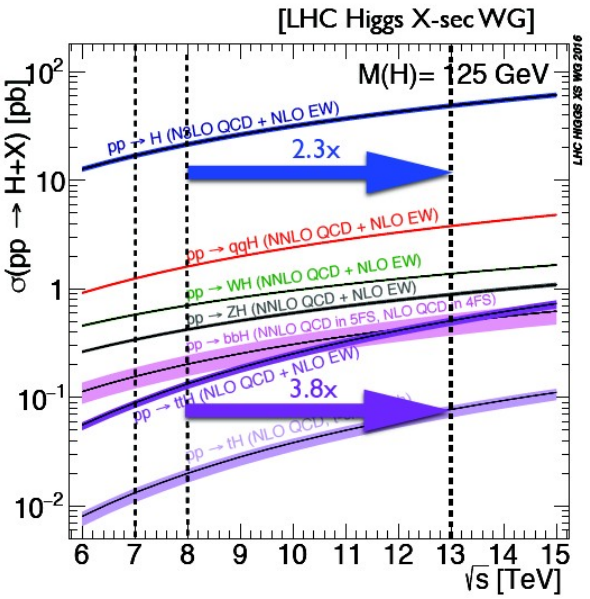
Direct probe *(tree-level diagrams)*

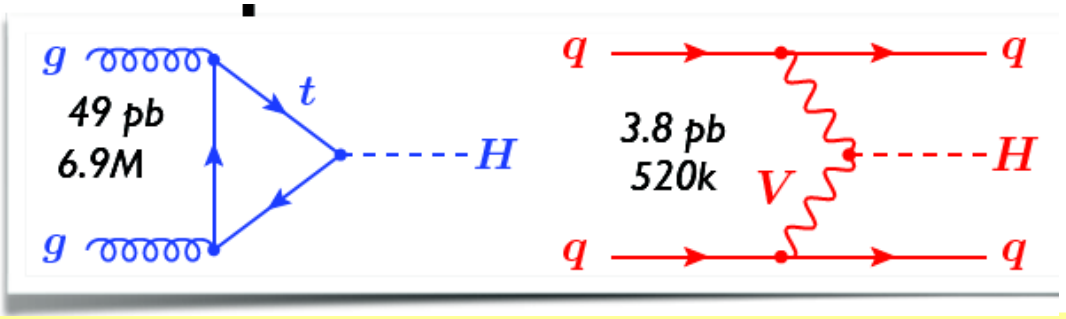


	3rd gen.
Leptons	$H \to \tau\tau$
Down-type quarks	$H \to b\bar{b}$
Up-type quarks	$t\bar{t}H$

- **Indirect measurements of y_t via ggF and $H \to \gamma\gamma$ loop**
  - particles entering loops
- **ttH → direct probe for top-Higgs Yukawa coupling y_t^2**
  - check of SM
- **Probe up-type quarks for the first time**

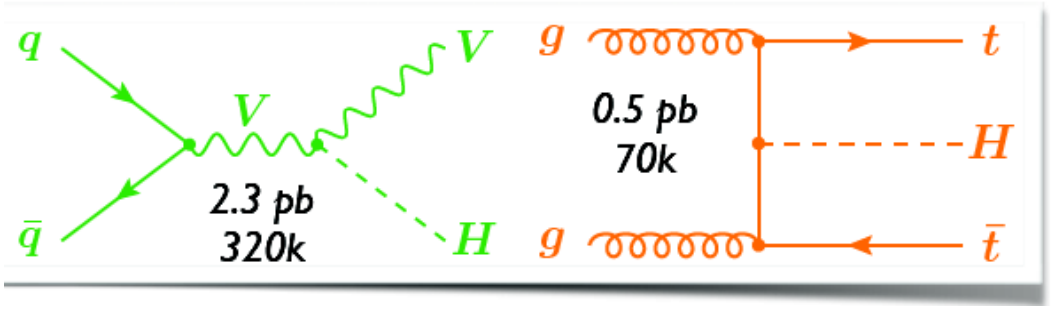
Higgs boson production and decay

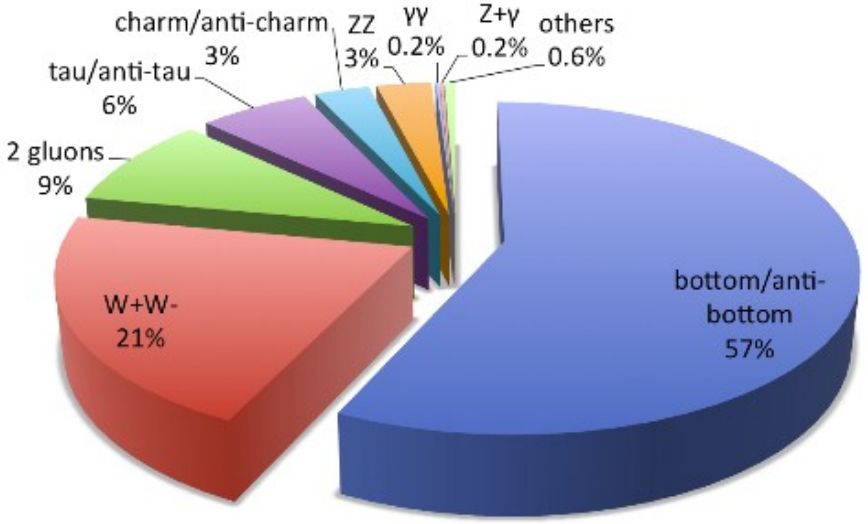




σ [pb]
#Higgs produced during Run-2

Increase in the Higgs boson production rate from Run I to Run II due to higher cm energy

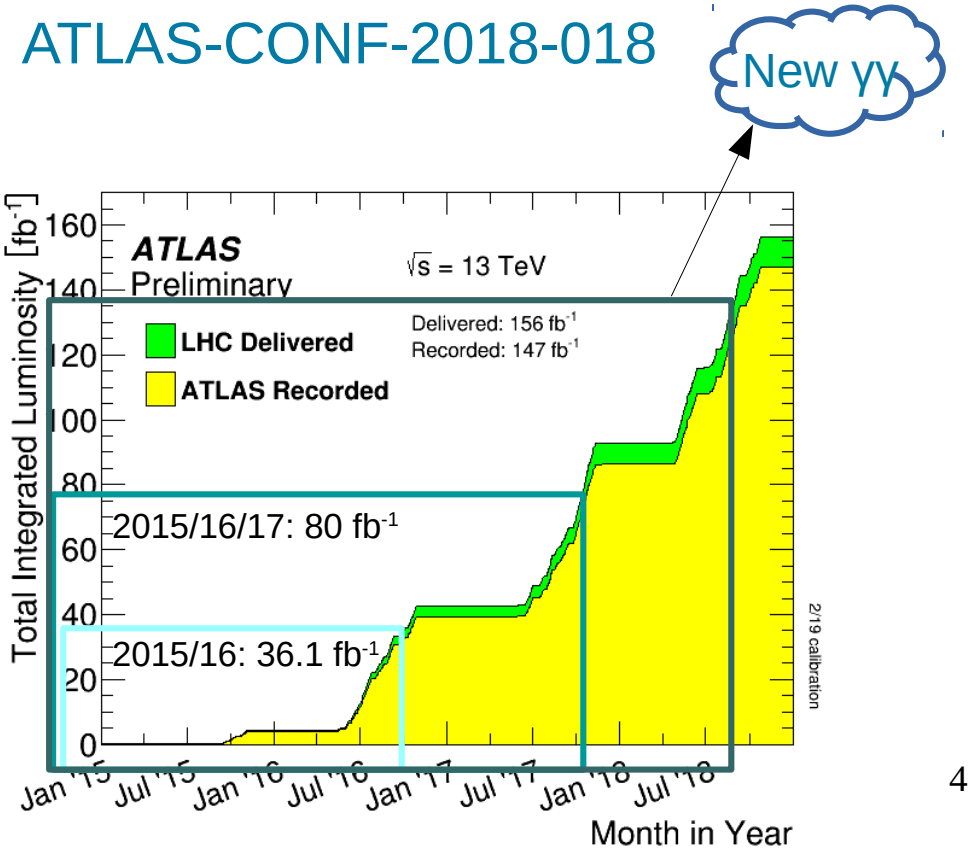




- **WW → high BR, low mass resolution**
- **bb, ττ → probe Higgs coupling to fermions, high BR but low signal senitivity**
- **ZZ , γγ → precise differential measurements due to high mass resolution channel mass**

Analyses included in this talk

- **Results with Full Run II 2015-2018: 138 fb^{-1}**
  - H($\gamma\gamma$): ATLAS-CONF-2019-004
- **Results with 2015-2017: 80 fb^{-1}**
  - ttH: PLB 784 (2018) 173
  - H($\gamma\gamma$):ATLAS-CONF-2019-005, ATLAS-CONF-2018-028
  - H($ZZ \rightarrow 4l$): ATLAS-CONF-2019-005, ATLAS-CONF-2018-018
- **Results with 2015-2016: 36 fb^{-1}**
  - ttH(ML): PRD 97 (2018) 072003
  - ttH(bb): PRD 97 (2018) 072016

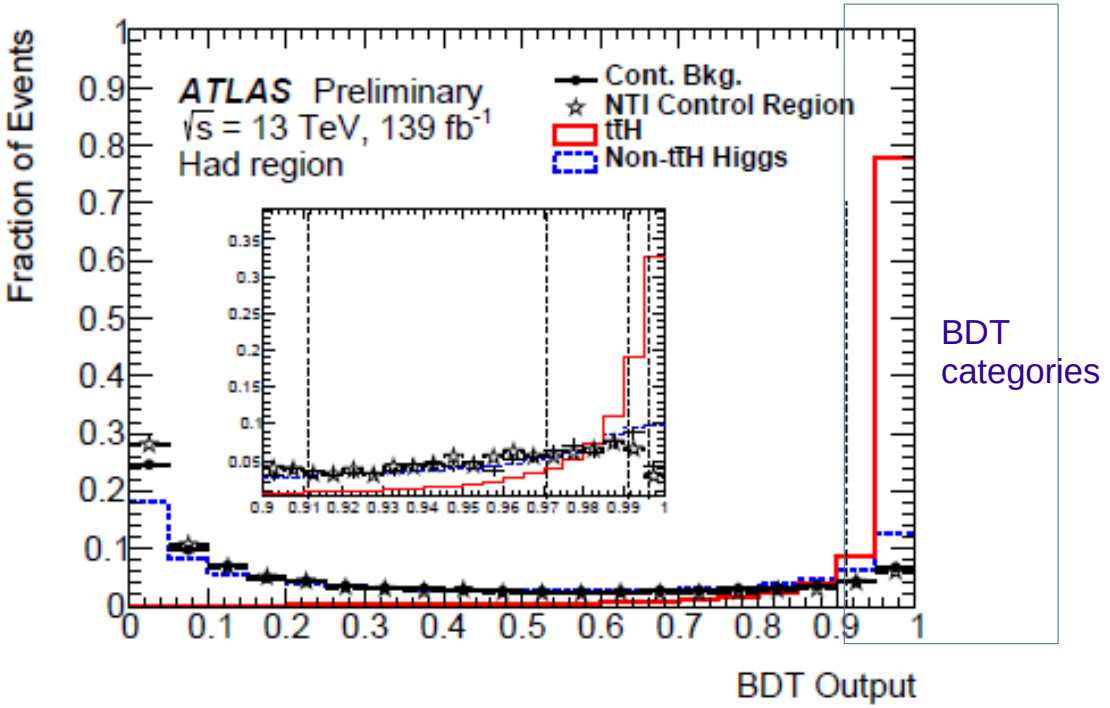


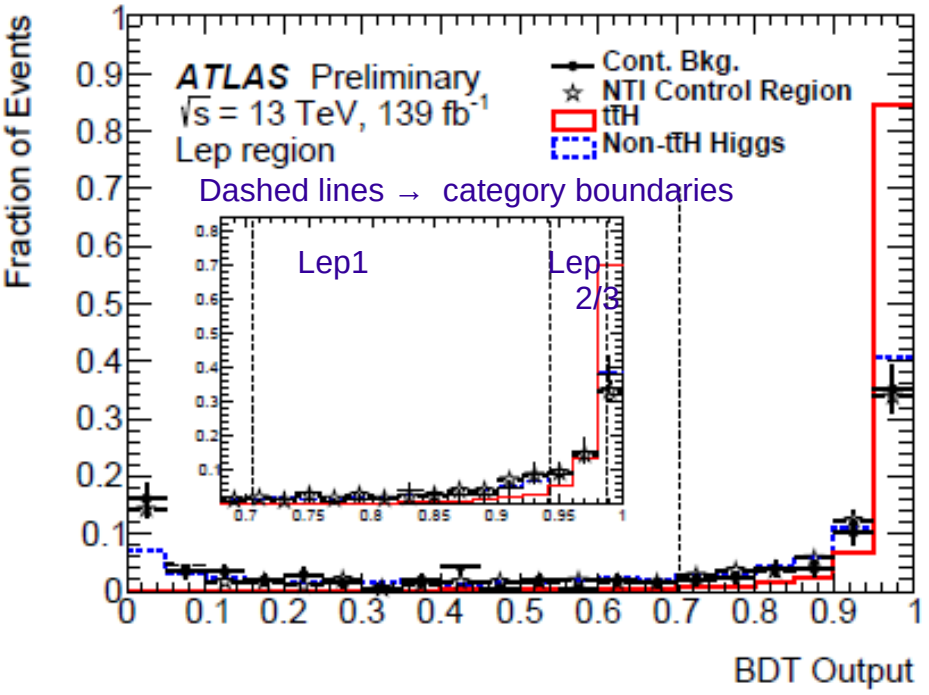
μ = observed cross section times the branching ratio (σ × BR), divided by the predicted SM cross section times the SM branching ratio ($\sigma_{SM} \times BR_{SM}$).

139 fb $^{-1}$

ttH(γγ):Introduction

- The “Lep” region → targeting tt decays in which at least one of the W bosons decays to a μ/e,≥ 1 isolated lepton + ≥1 jet with p_T > 25 GeV, b-hadron tagged.
- The “Had” region → targets hadronic top decays: ≥1 jet with p_T > 25 GeV, b-hadron tagged + ≥2 additional jets with p_T > 25 GeV and no reconstructed leptons.

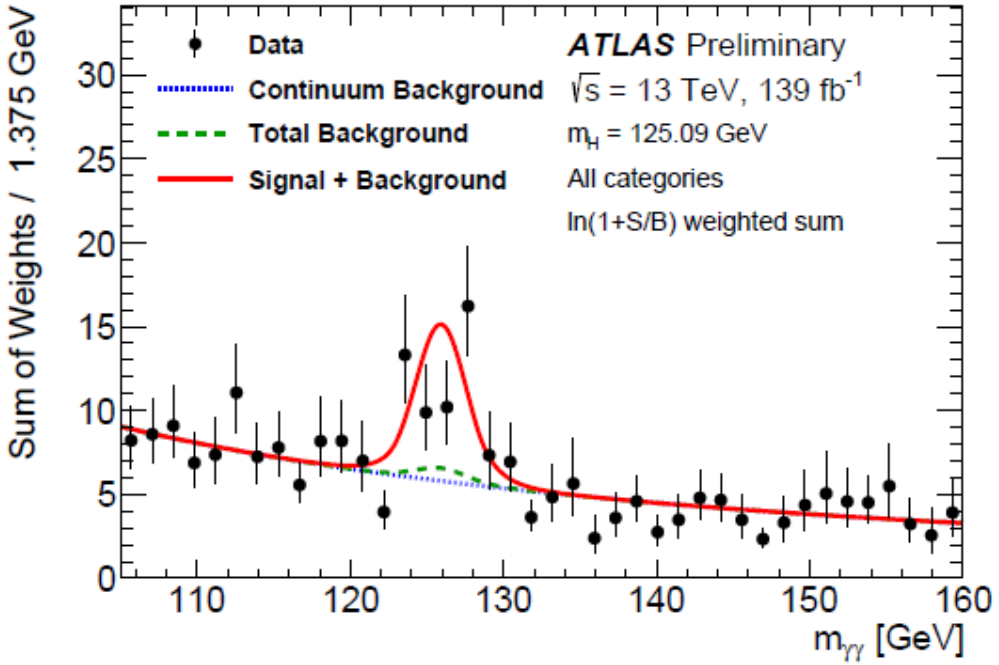


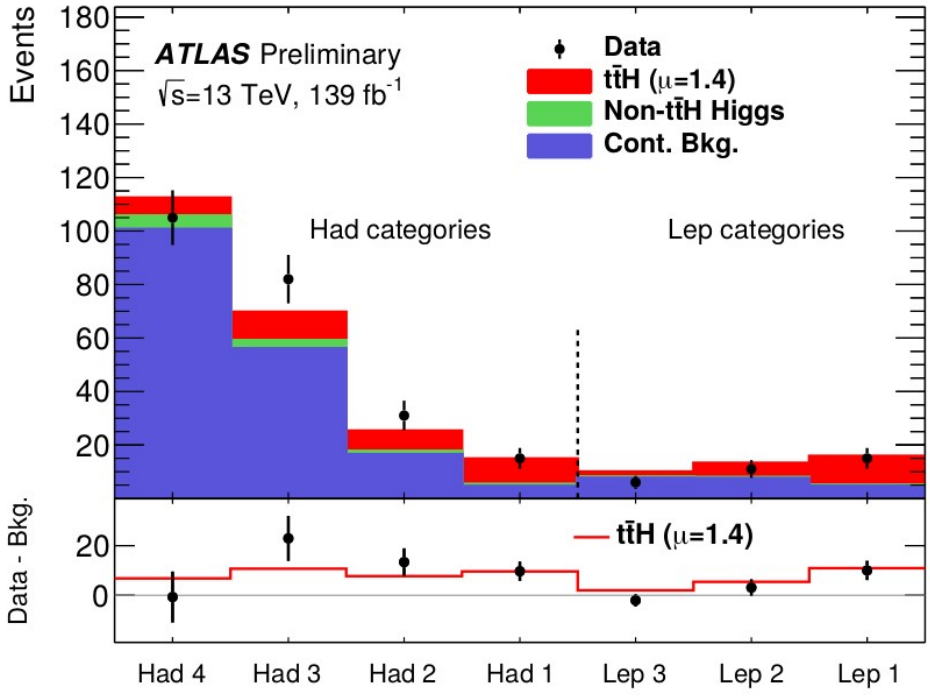


- Boosted decision tree (BDT) dedicated to “Lep” / “Had”, trained with the XGBoost to create regions of high ttH signal purity.
  - Inputs include: photon kinematics ($p_T/m_{\gamma\gamma}$, η,ϕ), E_T^{miss} ,E for up to 4(2) leading jets(lep) in p_T
  - Backgrounds: γγ, tt+γγ (data in control regions), other Higgs prod (from simulation)

ttH(γγ): Results

- **Simultaneous unbinned fit of $m_{\gamma\gamma}$ (105-160 GeV) in all 7 categories**
  - ttH signal: double-sided crystal ball
  - Continuum background: smooth functions (power-law or exponential)





ttH(γγ): Results

- **Dominant uncertainties:**
  - Statistically dominated!

Uncertainty source	$\Delta\sigma_{low}/\sigma$ [%]	$\Delta\sigma_{high}/\sigma$ [%]
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_T^{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

$$\mu_{t\bar{t}H} = 1.38\ ^{+0.41}_{-0.36} = 1.38\ ^{+0.33}_{-0.31}\ (\text{stat.})\ ^{+0.13}_{-0.11}\ (\text{exp.})\ ^{+0.22}_{-0.14}\ (\text{theo.}).$$

$$\sigma_{t\bar{t}H} \times B_{\gamma\gamma} = 1.59^{+0.43}_{-0.39}\ \text{fb} = 1.59^{+0.38}_{-0.36}\ (\text{stat.})\ ^{+0.15}_{-0.12}\ (\text{exp.})\ ^{+0.15}_{-0.11}\ (\text{theo.})\ \text{fb}.$$

SM:

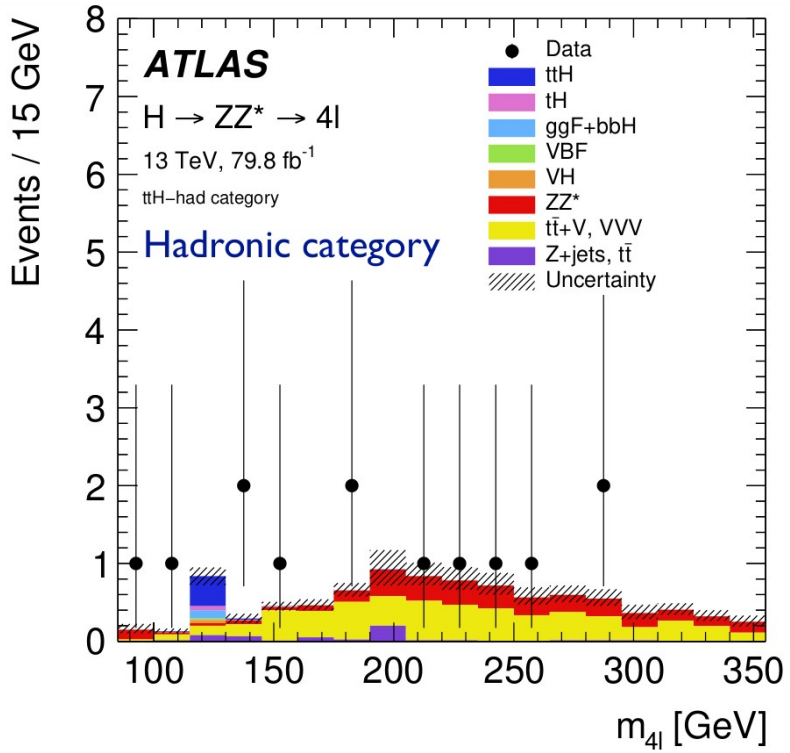
$$t\bar{t}H(\rightarrow \gamma\gamma) = 1.15^{+0.09}_{-0.12}\ \text{fb}.$$

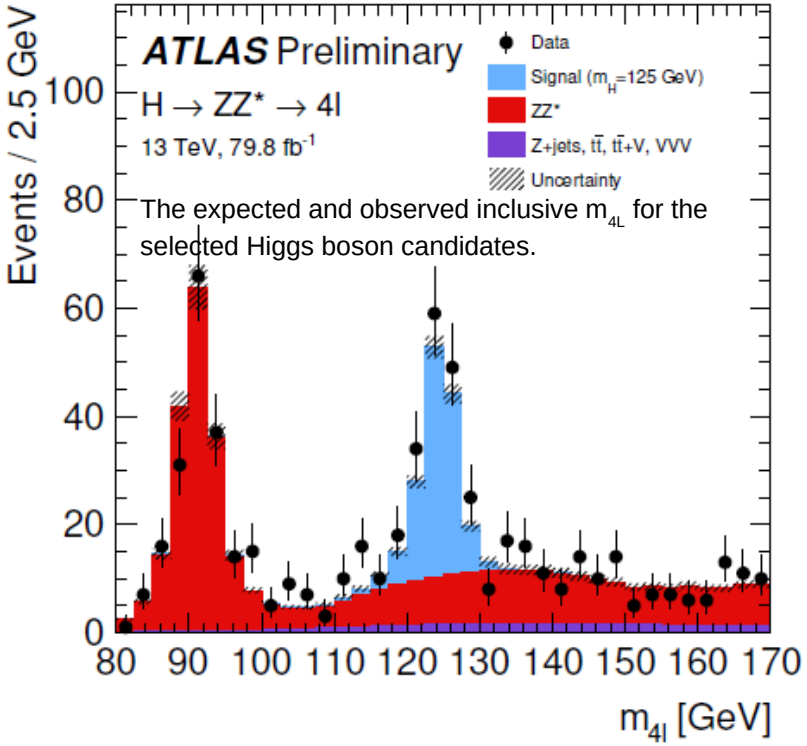
- **The combined observed significance is 4.9σ (4.2σ expected)**

79.8 fb^{-1}

ttH(ZZ* → 4l) Introduction

- ≥4 isolated leptons (=e, μ) , common vertex, 2 pairs of Same Flavour Opposite Sign leptons, 115 GeV < m_{4L} < 130 GeV
- **Increase the expected ttH significance:**
  - "Had" → hadronic top-quark decays, ≥3 additional jets + zero additional isolated leptons + BDT(E_T^{miss}, p_T^{jj}, N_{jets}, N_{b-jets}, H_T, $\mathcal{M}_{sig}$)
  - "Lep" → semileptonic top-quark decays, ≥1 additional jet, ≥1 additional isolated lepton.
- **Main backgrounds:**
  - ttV + non-ttH (ggF + tH for the Had and tH for the Lep region), estimated from simulation.

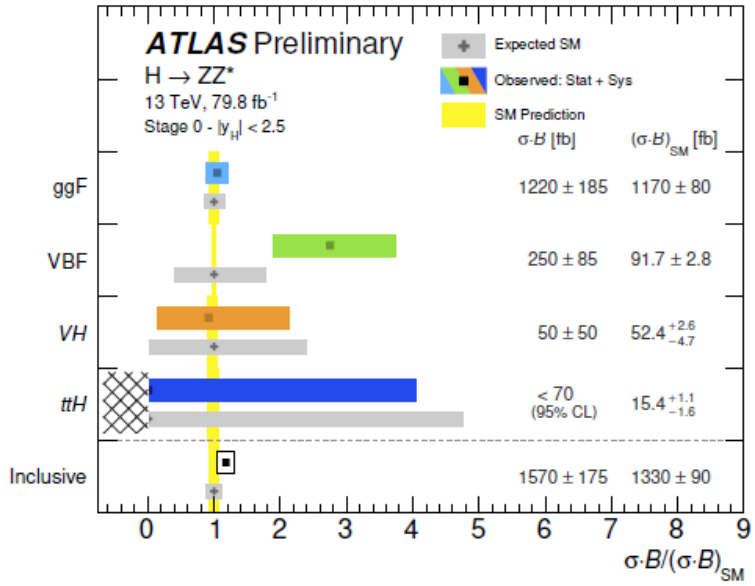




ttH(ZZ* → 4l) Results

- **No event is observed in ttH, expect 1.1 events (0.6 ttH)**

Production bin	Cross section ($\sigma \cdot \mathcal{B}$) [pb]		$(\sigma \cdot \mathcal{B})/(\sigma \cdot \mathcal{B})_{\mathrm{SM}}$
	SM expected	Observed	Observed
Inclusive production, $\lvert y_H \rvert < 2.5$			
	1.33 ± 0.09	$1.57 \pm 0.16 \pm 0.07 \pm 0.04$	$1.18 \pm 0.12 \pm 0.05 \pm 0.03$
Stage-0 production bins, $\lvert y_H \rvert < 2.5$			
ggF	1.17 ± 0.08	$1.22 \pm 0.17 \pm 0.07 \pm 0.04$	$1.04 \pm 0.14 \pm 0.06 \pm 0.03$
VBF	0.0917 ± 0.0028	$0.25 \pm 0.08 \pm 0.02 \pm 0.01$	$2.8 \pm 0.9 \pm 0.2 \pm 0.2$
VH	$0.0524^{+0.0026}_{-0.0047}$	$0.05 \pm 0.05 \pm 0.01 \pm 0.01$	$0.9 \pm 1.0 \pm 0.1 \pm 0.1$
ttH	$0.0154^{+0.0011}_{-0.0016}$	< 0.07	< 4.04

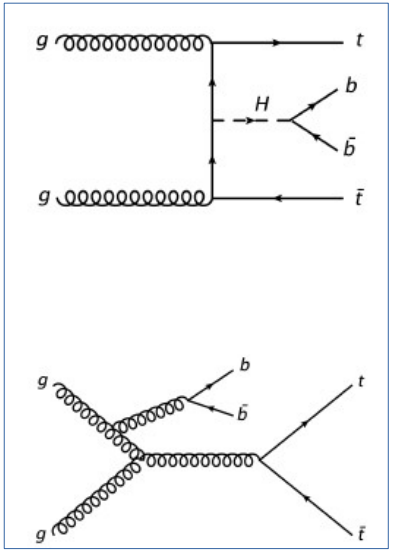


Measurement	Experimental uncertainties [%]				Theory uncertainties [%]				
	Lum.	e, μ, pile-up	Jets, flavour tagging	Reducible backgr.	ZZ^* backgr.	PDF	QCD scale	Signal Parton Shower	Composition
Stage-0 production bin cross sections									
ggF	2.9	3.9	1.3	0.7	2.3	0.4	2.1	0.7	-
VBF	1.7	1.5	10.5	0.5	2.3	2.3	9.5	5.1	-
VH	2.0	1.7	7.8	1.8	5.6	2.1	14.9	3.1	-
ttH	2.5	1.9	3.9	1.5	1.9	0.3	8.8	9.6	-

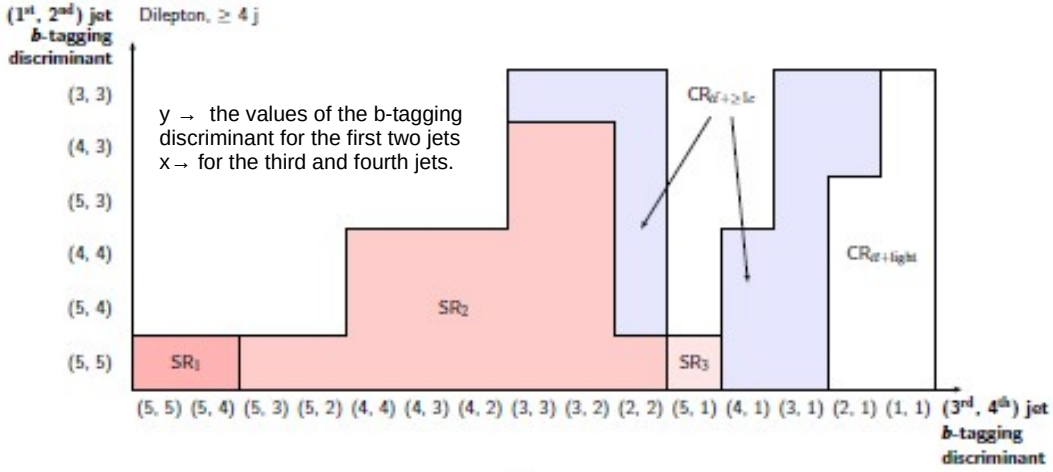
- Main systematic uncertainties
  - QCD scale
  - ttH PS
  - Jets,flavour tagging

36.1 fb^{-1}

ttH(bb): Introduction

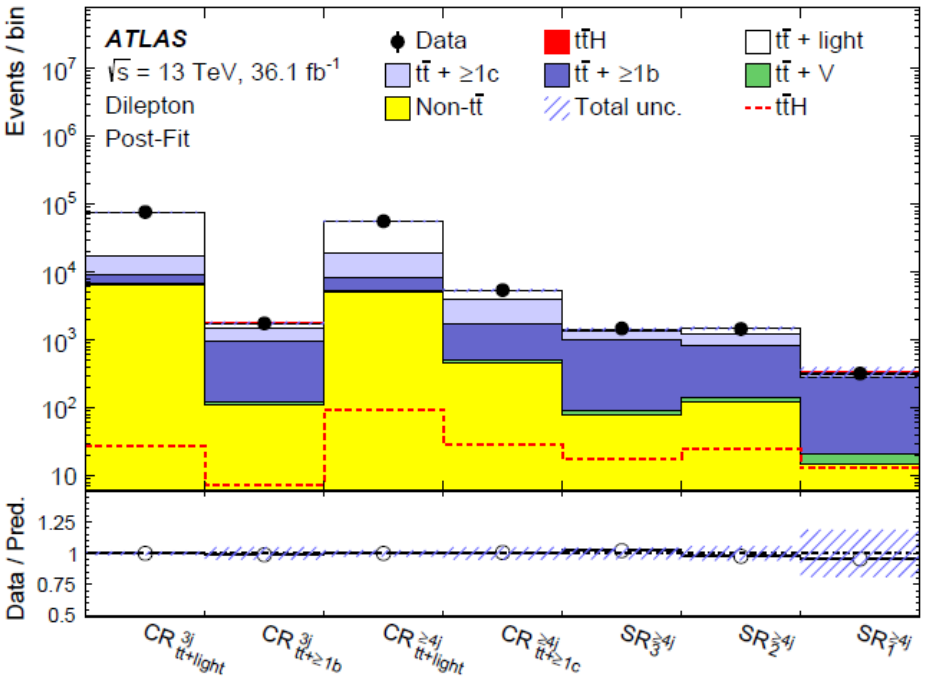


- **Targets the H → bb̄ decay mode.**
- **The selected events contain either one or two electrons/muons from the top-quark decays**
  - categorized according to the number of jets and how likely these are to contain b-hadrons.



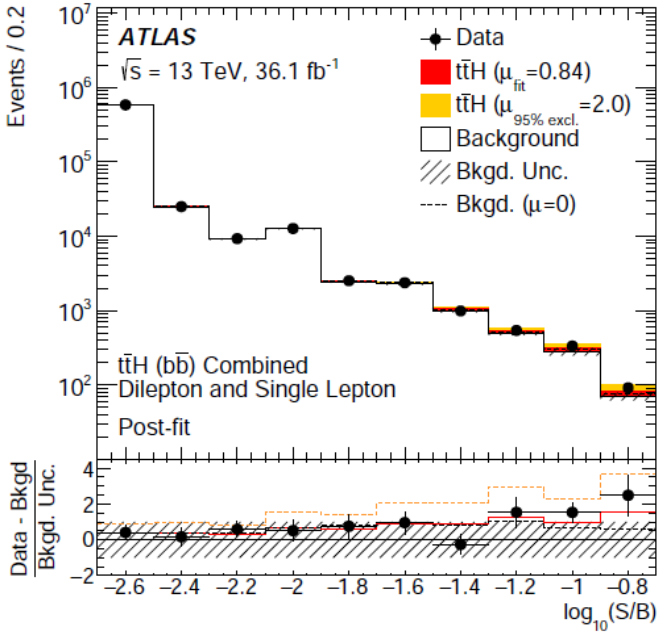
Analysis strategy: splitting events into categories according to Njet and Nbjet, CR enhanced in single background components ; reco BDT, classification BDT, fit.

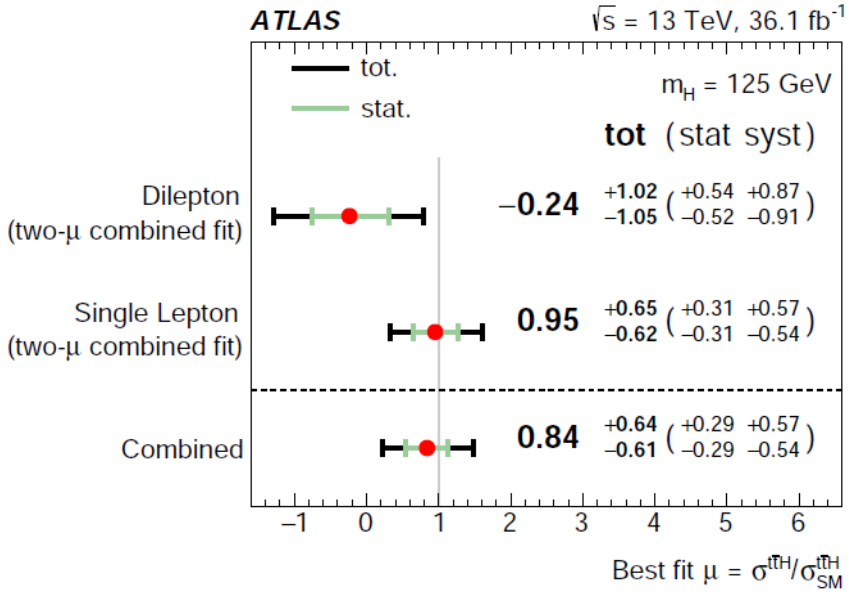
Comparison of predicted and observed event yields



ttH(bb) Results

$$\mu = 0.84 \pm 0.29\ (\text{stat.})\ ^{+0.57}_{-0.54}\ (\text{syst.}) = 0.84^{+0.64}_{-0.61}$$





Uncertainty source	$\Delta\mu$	
$t\bar{t}$ + ≥1b modeling	+0.46	−0.46
Background-model statistical uncertainty	+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
$t\bar{t}$ + ≥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
$t\bar{t}$ + ≥1b normalization	+0.09	−0.10
$t\bar{t}$ + ≥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

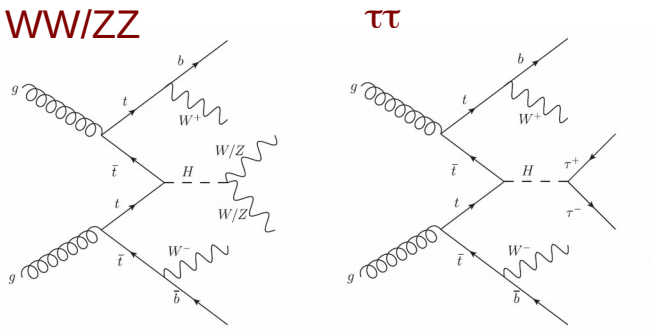
- Significance w.r.t bkg only hypothesis: 1.4 (1.6) obs.(exp.)
- Signal strength > 2 excluded at the 95% CL.
- The modeling of this background relied heavily on MC predictions.
  - Improvements expected

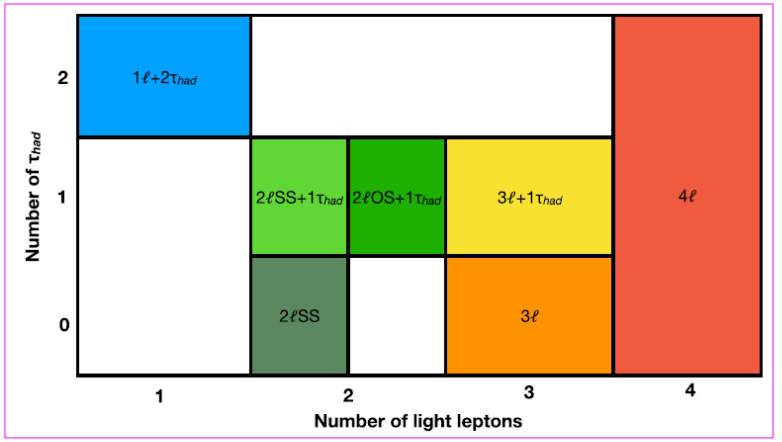
36.1 fb^{-1}

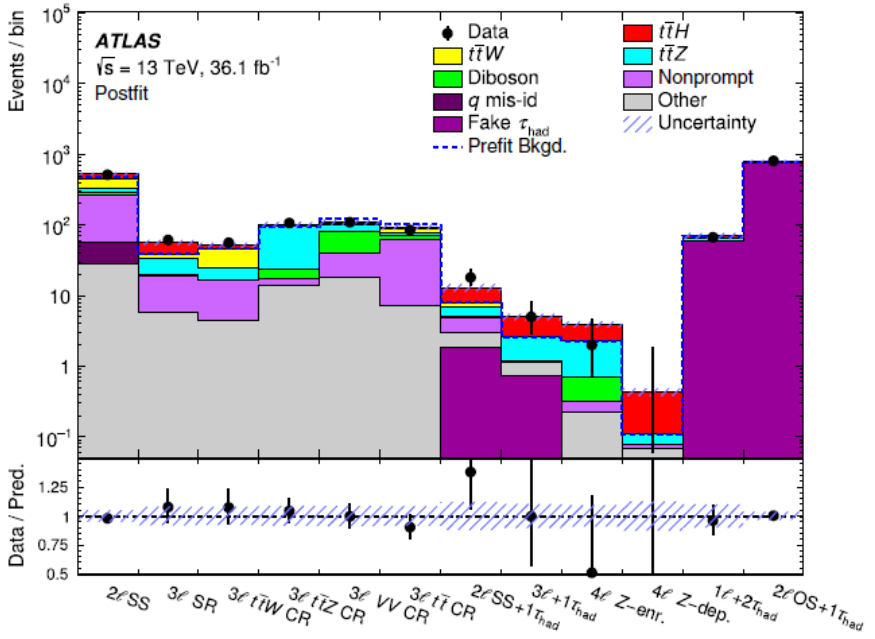
ttH multi-lepton: Intro

- Seven final states, categorized by the number and flavor of charged-lepton candidates

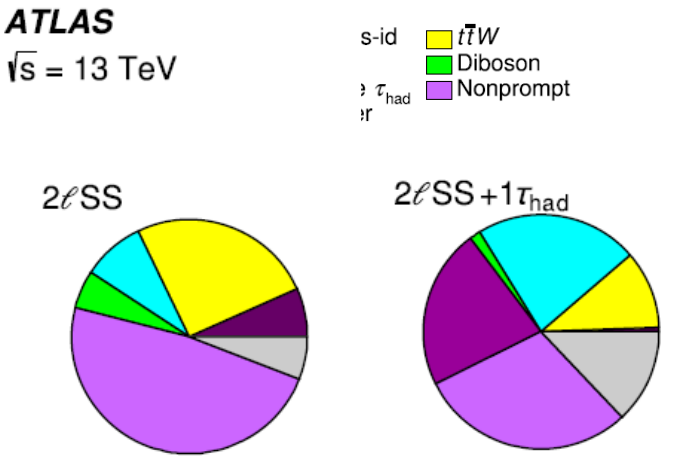
- Irreducible backgrounds (ttW, ttZ, …):
  - estimated from MC and validated in data
- Reducible backgrounds (non-prompt e/μ and fake τ_{had}):
  - data-driven techniques
- Multivariate techniques applied in most channels.





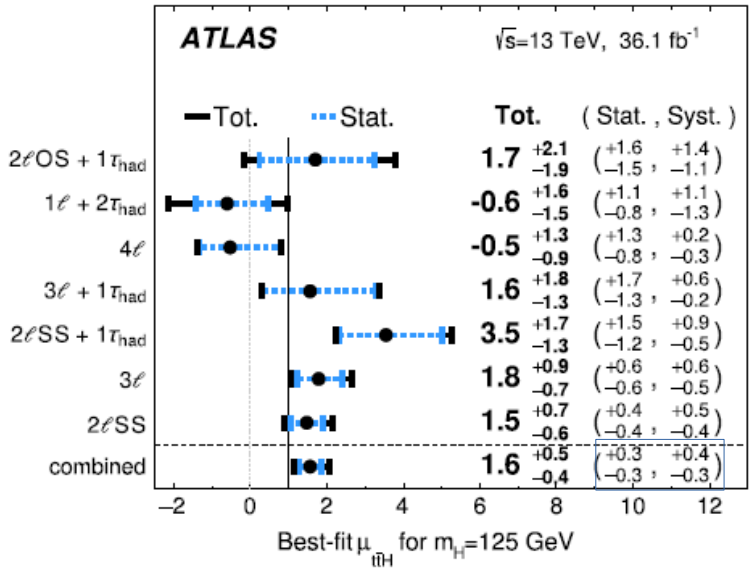


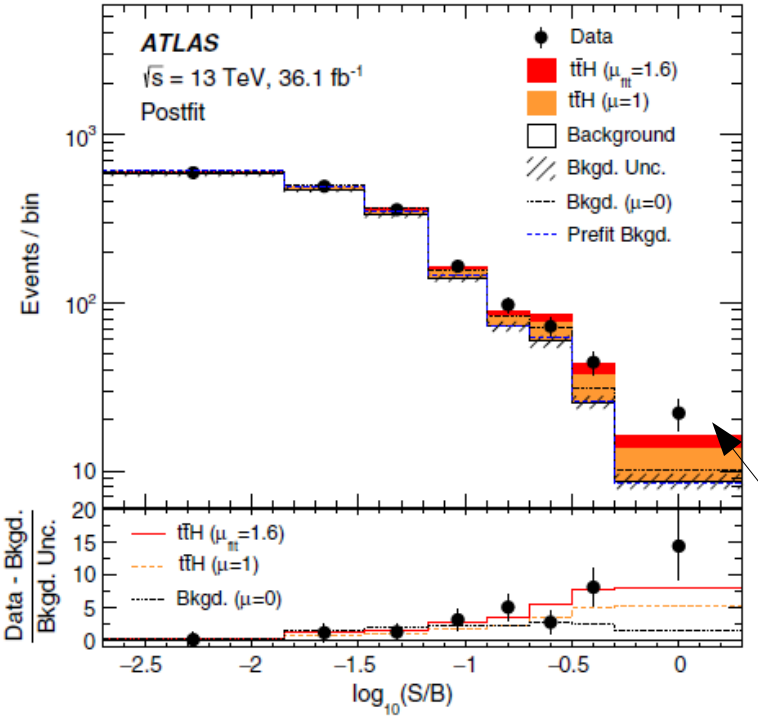
New Non-prompt lepton BDT & Charge misassignment veto BDT



- Signal is extracted with a binned profile likelihood fit across all categories including main background CR.

ttH multi-lepton: Results





- Significance w.r.t bkg only hypothesis for multilepton: 4.1 (2.8) obs.(exp.)
- Stats~sys

Uncertainty source	$\Delta\mu$	
$t\bar{t}H$ modeling (cross section)	+0.20	−0.09
Jet energy scale and resolution	+0.18	−0.15
Nonprompt 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

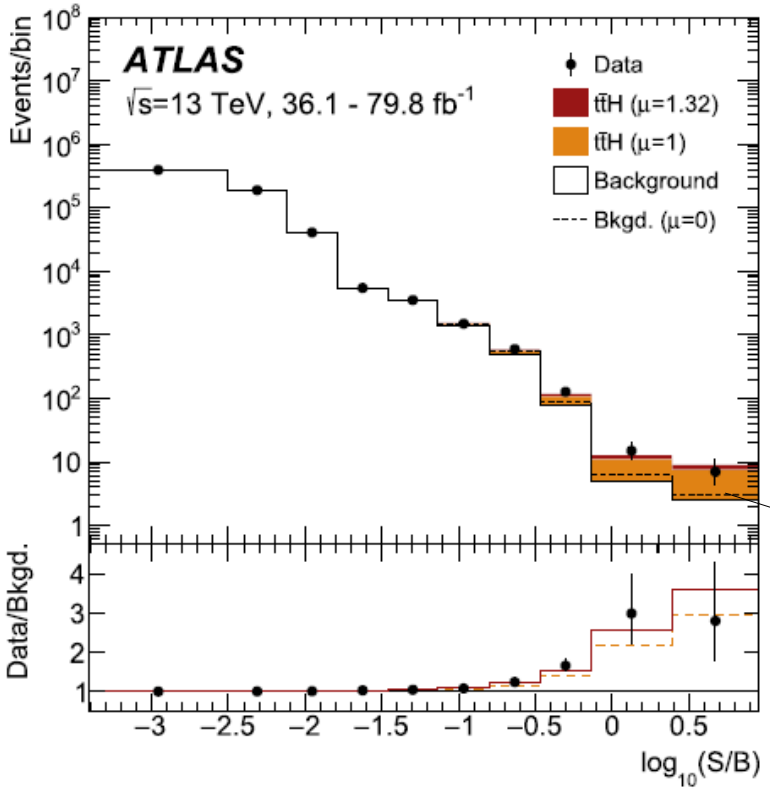
Excess in high S/B bins, consistent with ttH signal

ttH observation I

- **Observation of Higgs boson production in association with a top quark with the ATLAS detector!**
  - **6.3σ significance (5.1σ expected)**

Not updated to full Run II

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.)	4.1σ	3.7σ
$H \to$ multilepton	36.1	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)	4.1σ	2.8σ
$H \to b\bar{b}$	36.1	$400\ ^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)	1.4σ	1.6σ
$H \to ZZ^* \to 4\ell$	79.8	<900 (68% CL)	0σ	1.2σ
Combined (13 TeV)	36.1–79.8	670 ± 90 (stat.) $^{+110}_{-100}$ (syst.)	5.8σ	4.9σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	–	6.3σ	5.1σ



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	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-leptons	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4

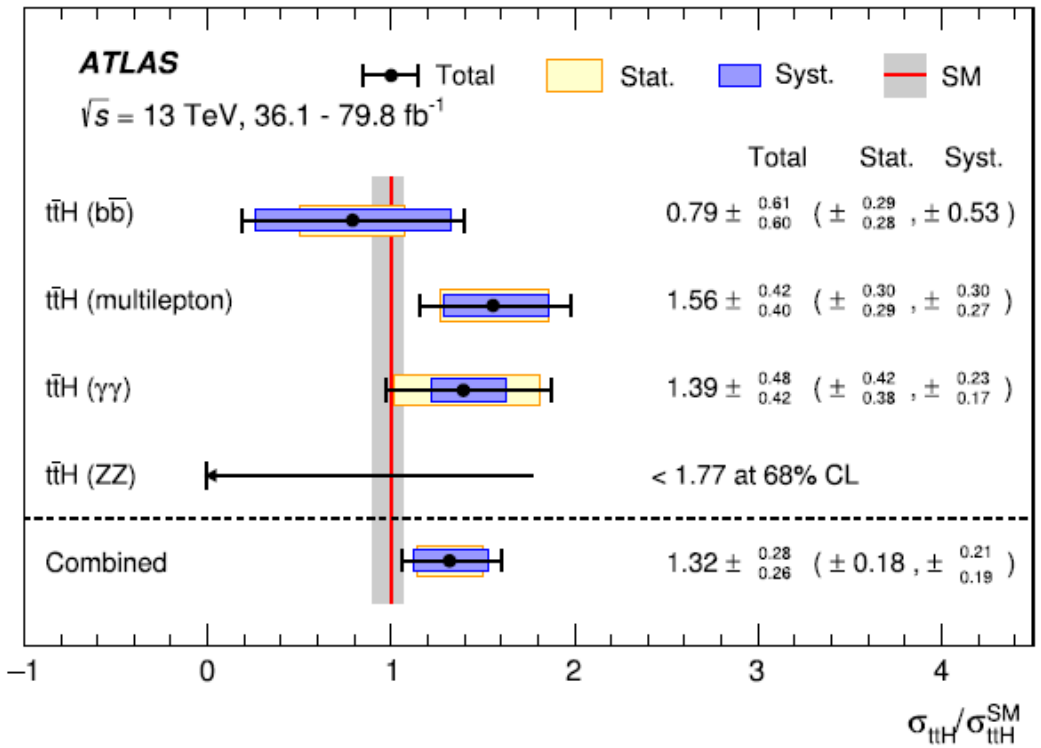
H → bb̄

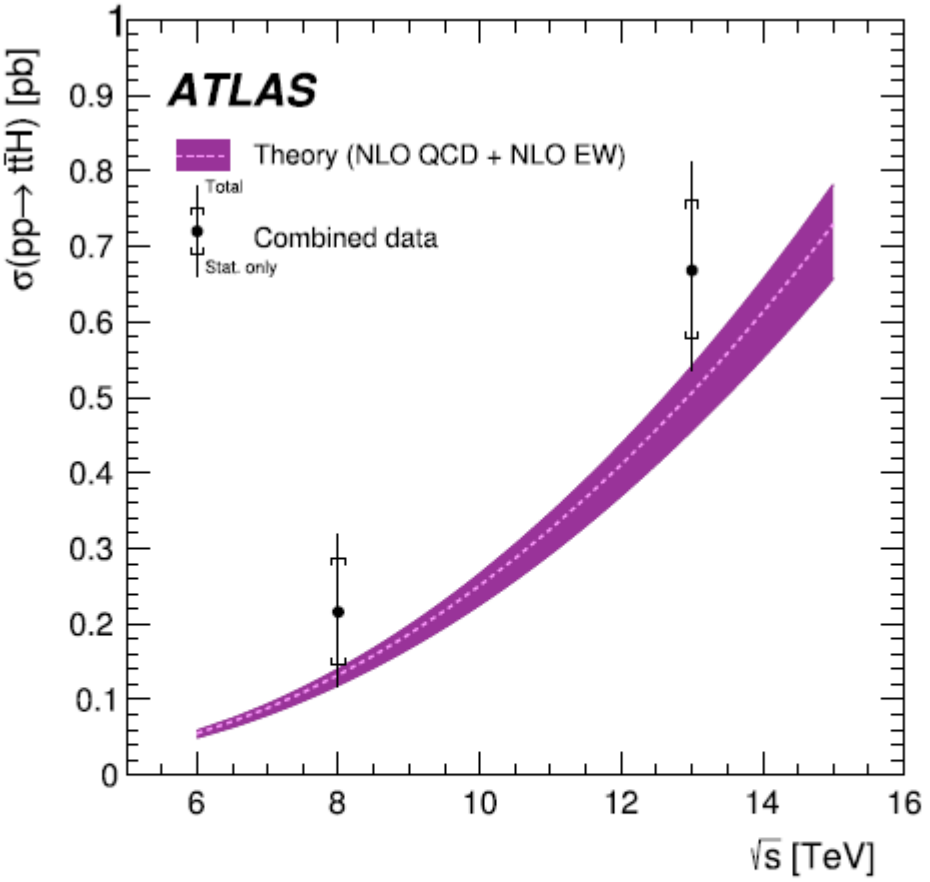
multilepton

H → bb̄ and multilepton

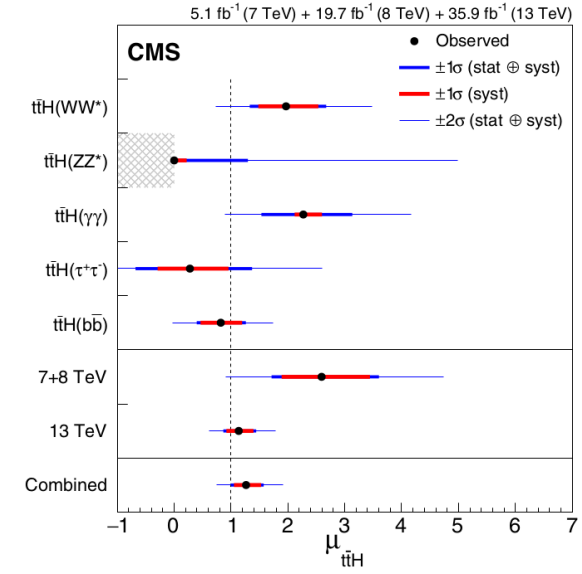
Excess in high S/B bins, consistent with ttH signal

ttH observation II





PhysRevLett.120.231801

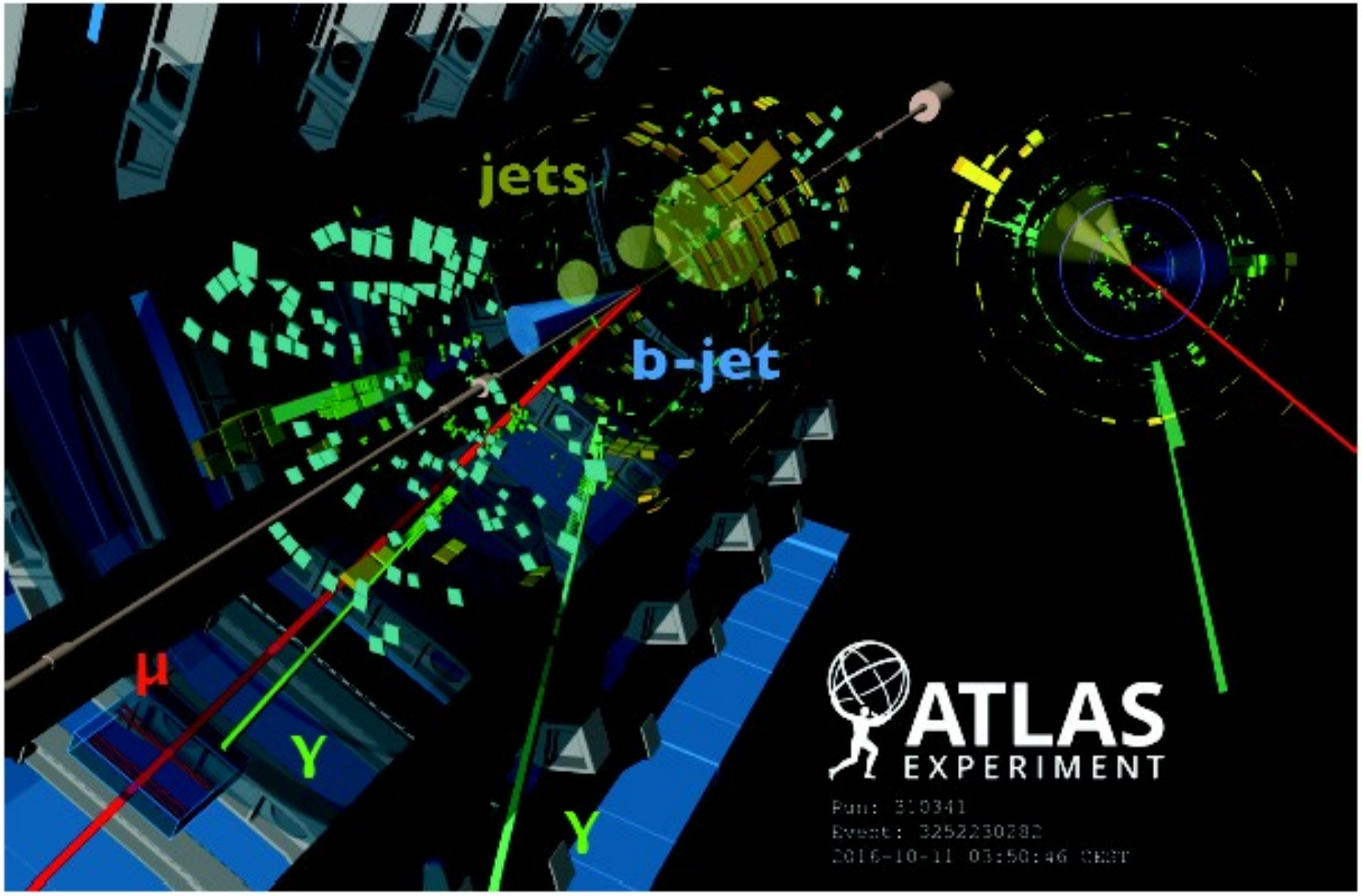


- Measurements consistent with SM prediction!
  - Combination is assuming SM branching ratios
- CMS also reported the observation of tt̄H production with a significance of 5.2 standard deviations.

Conclusions

- ATLAS Collaboration observed the ttH process:
  - **Run II + Run I: 6.3σ (5.1σ exp.)**
  - **Run II: 5.8σ (4.9σ exp.)**
    - **Not all analyses updated to full Run II luminosity!**
- Cross section measurements: in agreement with SM prediction.
- Measurement for 13 TeV:
  - $\sigma_{ttH}/\sigma^{SM}_{ttH} = 1.32 \pm {}^{0.28}_{0.26} \; (\pm 0.18 , \pm {}^{0.21}_{0.19})$
  - $\sigma_{ttH} = 670 \pm 90(stat.)^{+110}_{-100}(syst.) fb$
    - SM prediction: $579^{+35}_{-50} fb$
- CMS Collaboration: observation of ttH production.

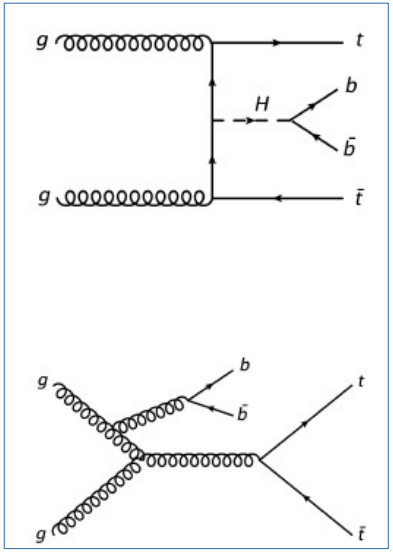
A data event from the ttH, H→γγ



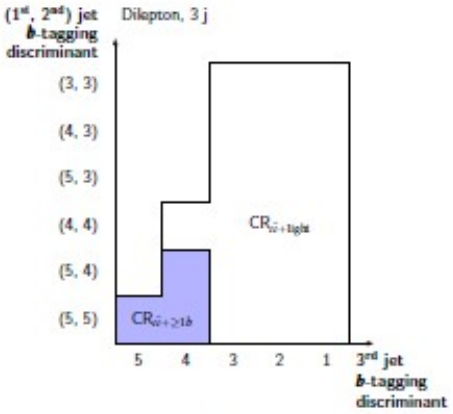
Backup Slides

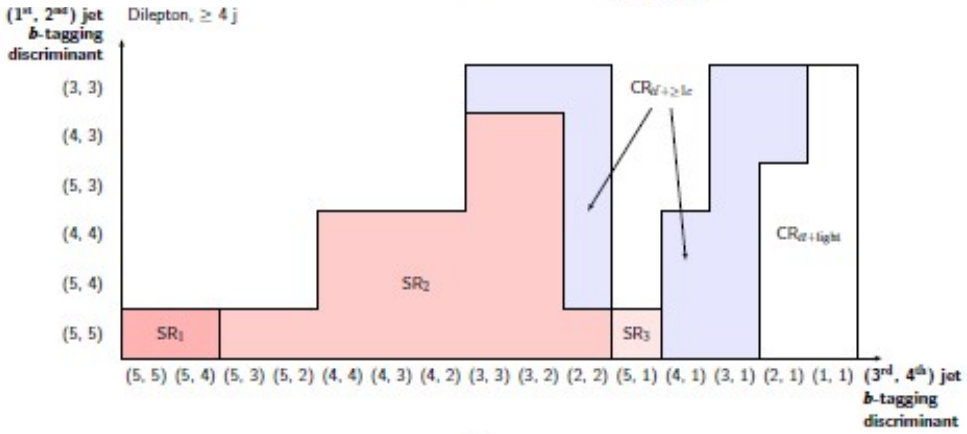
36.1 fb $^{-1}$

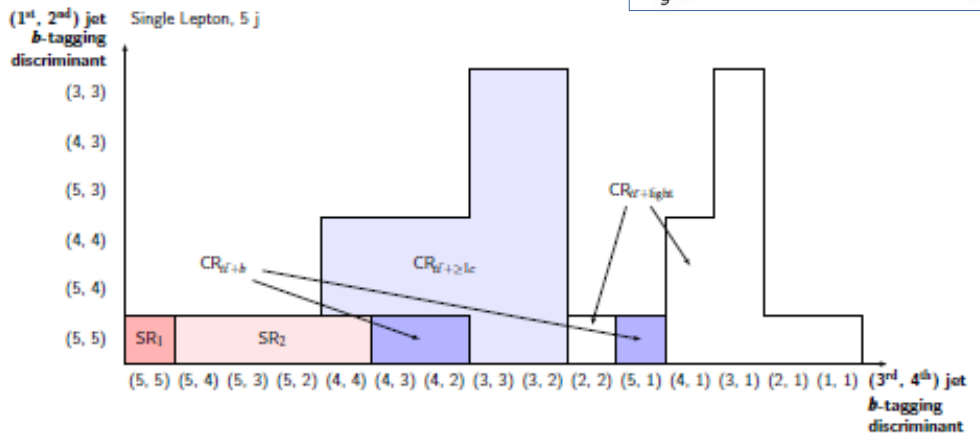
ttH(bb): Introduction

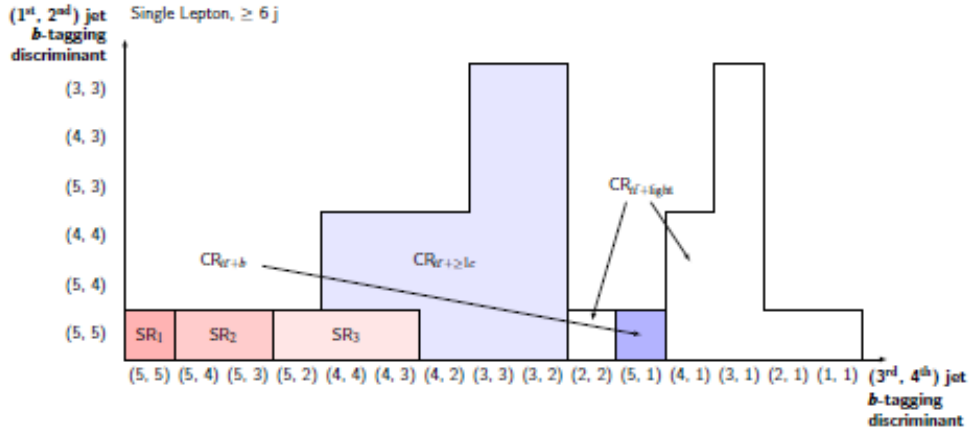


- **Targets the H → bb̄ decay mode.**
  - Explore the properties of the Higgs boson (p_T , η): going differential.
  - Probe the CP structure of the ttH interaction: BSM analysis.
- **The selected events contain either one or two electrons/muons from the top-quark decays**
  - categorized according to the number of jets and how likely these are to contain b-hadrons.
- **Multivariate techniques used to discriminate between s&b (dominated by tt+jets).**





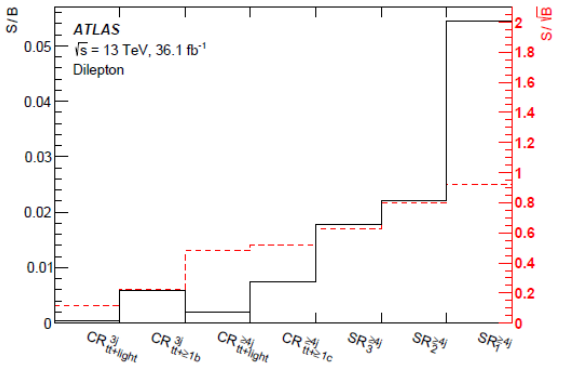


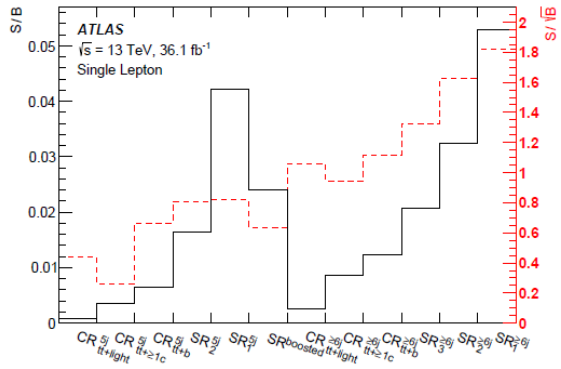


SR and CR the dilepton (left) and single-lepton (right) resolved channel
x → the values of the b-tagging discriminant for the first two jets, y → for the third and fourth jets.
The jets are ordered according to their value of the b-tagging discriminant in descending order.

Fractional contributions of the
various bkgd/total bkgd prediction

ttH(bb): S/B events

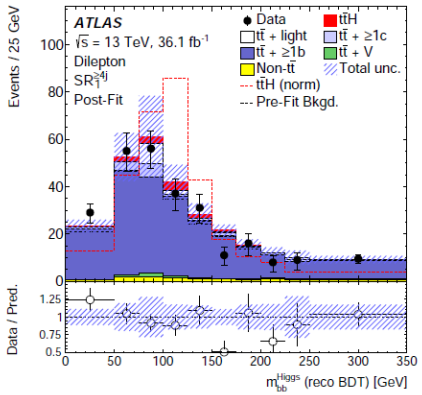


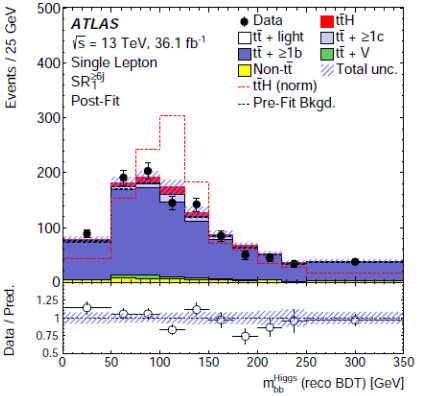


Comparison of predicted and observed event yields

H → bb decay:

- 89% of the ttH signal events in the SR of the dilepton channel
- 96% in the signal regions of the resolved single-lepton channel
- 86% in the boosted signal region

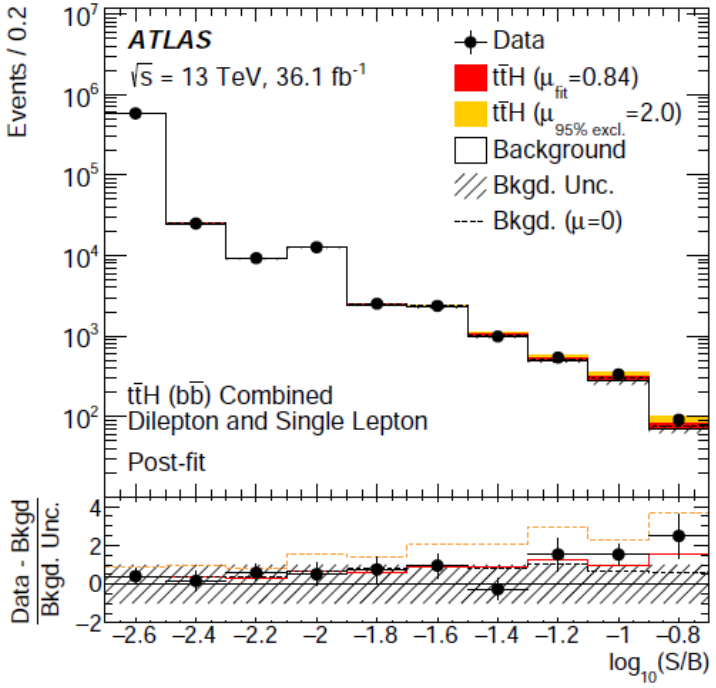


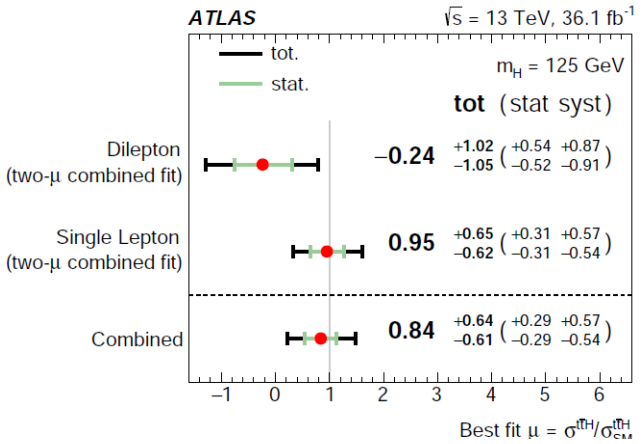


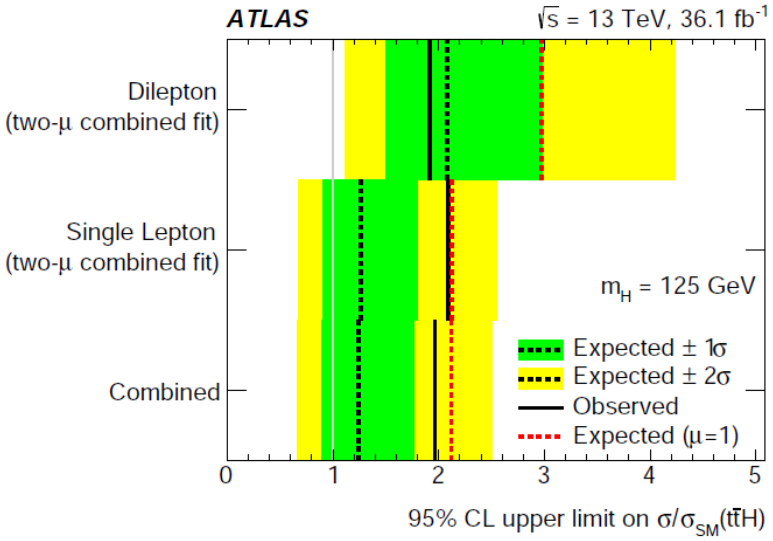
Comparison between data and prediction for the Higgs-boson candidate mass from the reconstruction BDT trained without variables involving the Higgs-boson candidate

ttH(bb) Results

$$\mu = 0.84 \pm 0.29\ (\text{stat.})\ ^{+0.57}_{-0.54}\ (\text{syst.}) = 0.84^{+0.64}_{-0.61}$$



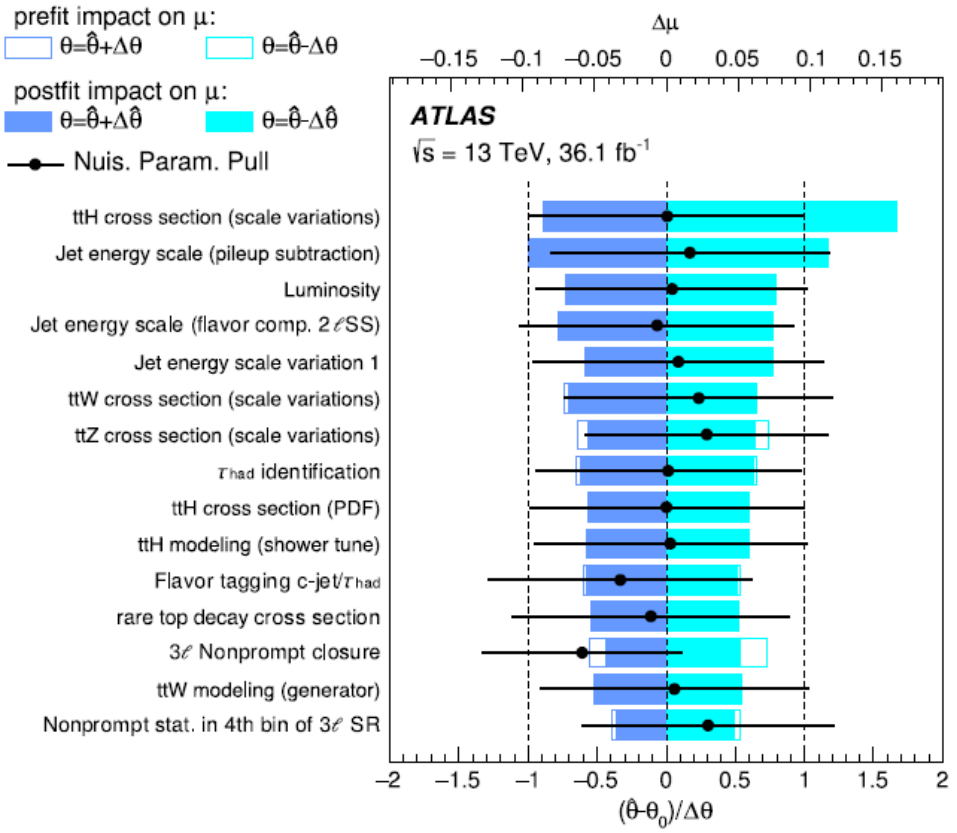




Uncertainty source	$\Delta\mu$	
$t\bar{t}$ + ≥1b modeling	+0.46	−0.46
Background-model statistical uncertainty	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modeling	+0.22	−0.05
$t\bar{t}$ + ≥1c modeling	+0.09	−0.11
JVT, pileup 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
$t\bar{t}$ + ≥1b normalization	+0.09	−0.10
$t\bar{t}$ + ≥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

- Significance w.r.t bkg only hypothesis: 1.4 (1.6) obs.(exp.)
- Signal strength > 2 excluded at the 95% CL.

- The modeling of this background relied heavily on MC predictions.
  - Related systematics have the highest impact on the ttH(bb) measurement.
  - Improving the tt modeling is a major focus for the new analysis round.



ttH multi-lepton

- Signal is extracted with a binned profile likelihood fit across all categories including main background CR.
- Main systematic uncertainties
  - ttH modelling (cross section)
  - Jet energy scale/resolution
  - Non-prompt e/μ estimates