GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Measurement of the $t\bar{t}H$ production

Johannes Mellenthin

On behalf of the ATLAS Collaboration

II. Physikalisches Institut, Georg-August-Universität Göttingen

Particle Physics I **ICPPA-2018** Moscow, October 23rd, 2018

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BMBF-Forschungsschwerpunkt ATLAS-EXPERIMENT
Physik bei höchsten Energien mit dem ATLAS-Experiment am LHC
FSP 103 ATLAS

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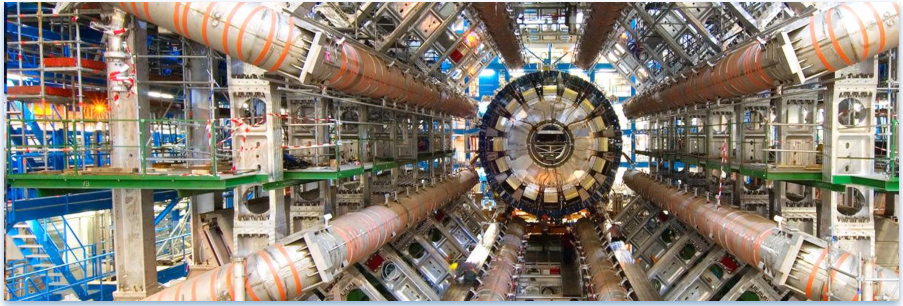
Introduction

- Observing $t\bar{t}H$ production is one of the milestones for LHC Run-II
- Direct sensitivity to top quark Yukawa coupling
- ATLAS (and CMS) have searched for $t\bar{t}H$ production since LHC Run-I
- Both experiments observed this process this year
- Presenting here an overview of the 13 TeV $t\bar{t}H$ ATLAS analyses

Outline

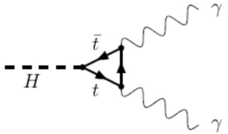
- $t\bar{t}H$ production and decay
- Run-II results
  - $t\bar{t}H$ ($H \rightarrow b\bar{b}$)
  - $t\bar{t}H$ (multilepton)
  - $t\bar{t}H$ ($H \rightarrow \gamma\gamma$)
  - $t\bar{t}H$ ($H \rightarrow ZZ^* \rightarrow 4\ell$)

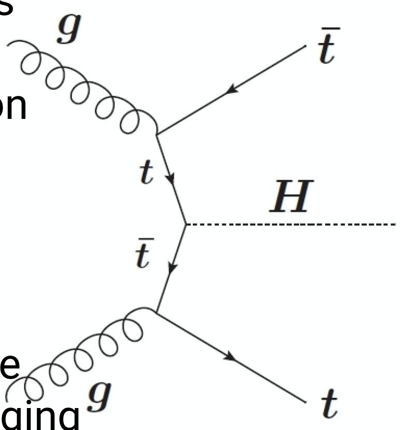


- Run-II combination of all channels
- Conclusions & Outlook

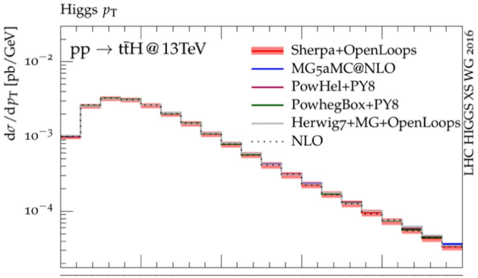
$t\bar{t}H$ production

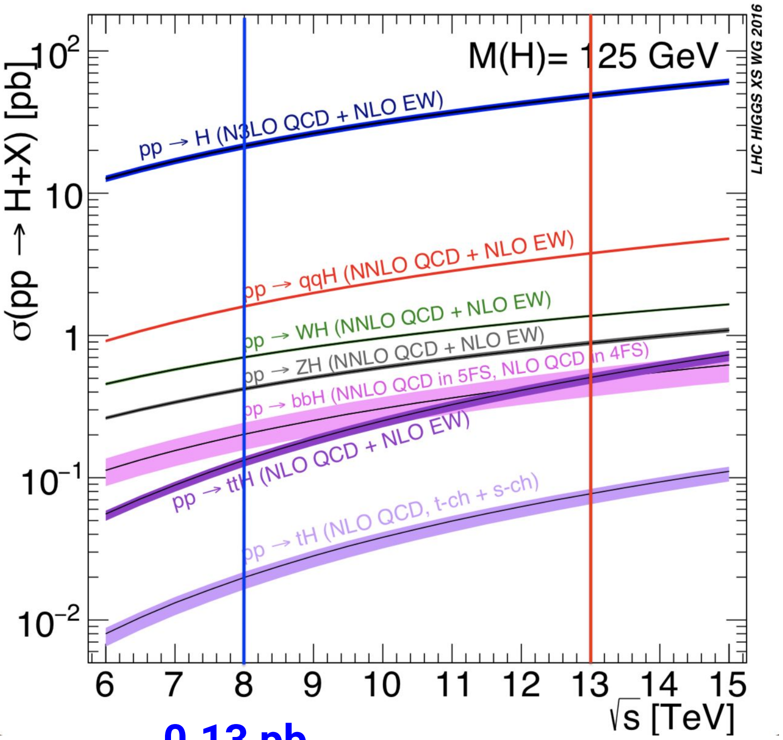
- Direct sensitivity to top quark Yukawa coupling
  - $m_H < 2 \cdot m_t \rightarrow$ SM Higgs cannot decay into $t\bar{t}$!
  - $H \rightarrow \gamma\gamma$ req. assumption on loop content





- Rare Higgs production mode
  - Experimentally challenging
  - S/B increases with centre-of-mass energy
- Several MC generators available
  - NLO in QCD + PS
  - Generators in good agreement





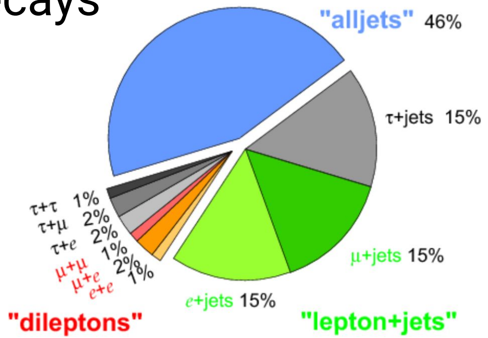
0.13 pb

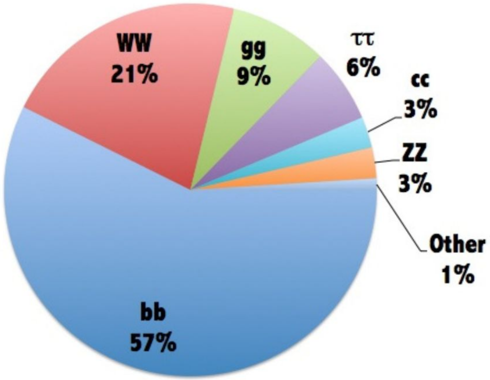
0.50 pb

$t\bar{t}H$ decay

- Different event topologies depending on top and Higgs decays
- $t\bar{t}$: allhad, ℓ+jets, dilepton
  - All hadronic highest BR, but larger backgrounds
- The main Higgs decay channels are used
  - $H \to b\bar{b}$, W^+W^-, ZZ^*, $\tau\tau$, $\gamma\gamma$
  - Analyses are split as follows
    - $t\bar{t}H$ ($H \to b\bar{b}$) - *the abundant*
    - $t\bar{t}H$ (multilepton) - *the small*
    - $t\bar{t}H$ ($H \to \gamma\gamma$) - *the other small*
    - $t\bar{t}H$ ($H \to ZZ^* \to 4\ell$) - *the tiny* (only since Run-II)
- Final states: ≥ 2 jets, ≥ 2 b-jets, 0-6 e/μ/τ, 0/2γ

BR vs resolution!



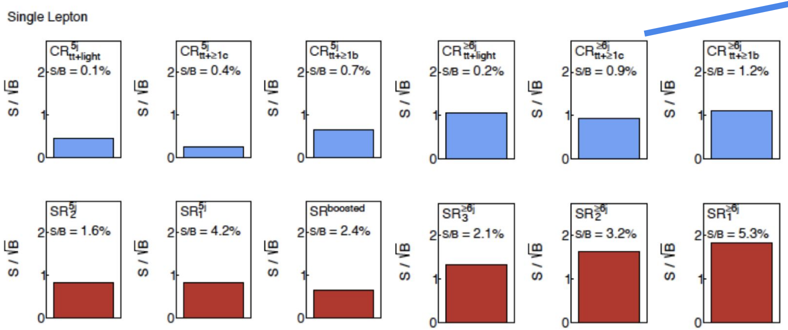


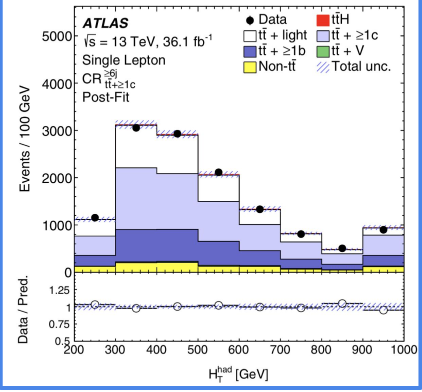
$t\bar{t}H$ analyses in Run-II

$t\bar{t}H$ ($H \to b\bar{b}$) analysis with 2015+2016 data

- $H \to b\bar{b}$ (highest BR) & split channels by $t\bar{t} \to 1\ell/2\ell$ (only e, μ)
- $t\bar{t}$+jets very challenging background
- Create SRs & CRs enriched in $t\bar{t}H$, $t\bar{t}b$, $t\bar{t}c$, $t\bar{t}$+light quarks
  - Defined by # jets & # b-tagged jets
  - Include lepton+jets boosted region

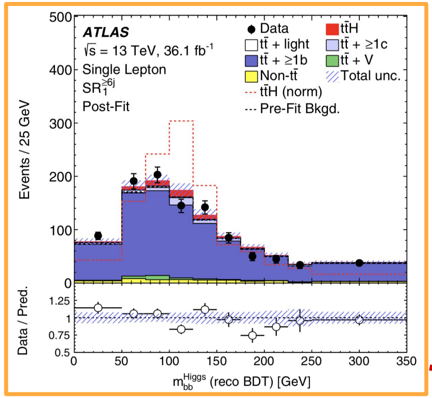
CR: H_T dist. or total yield



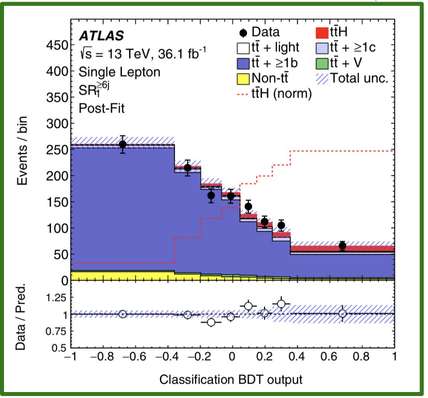


Constrain BKG in fit

SR



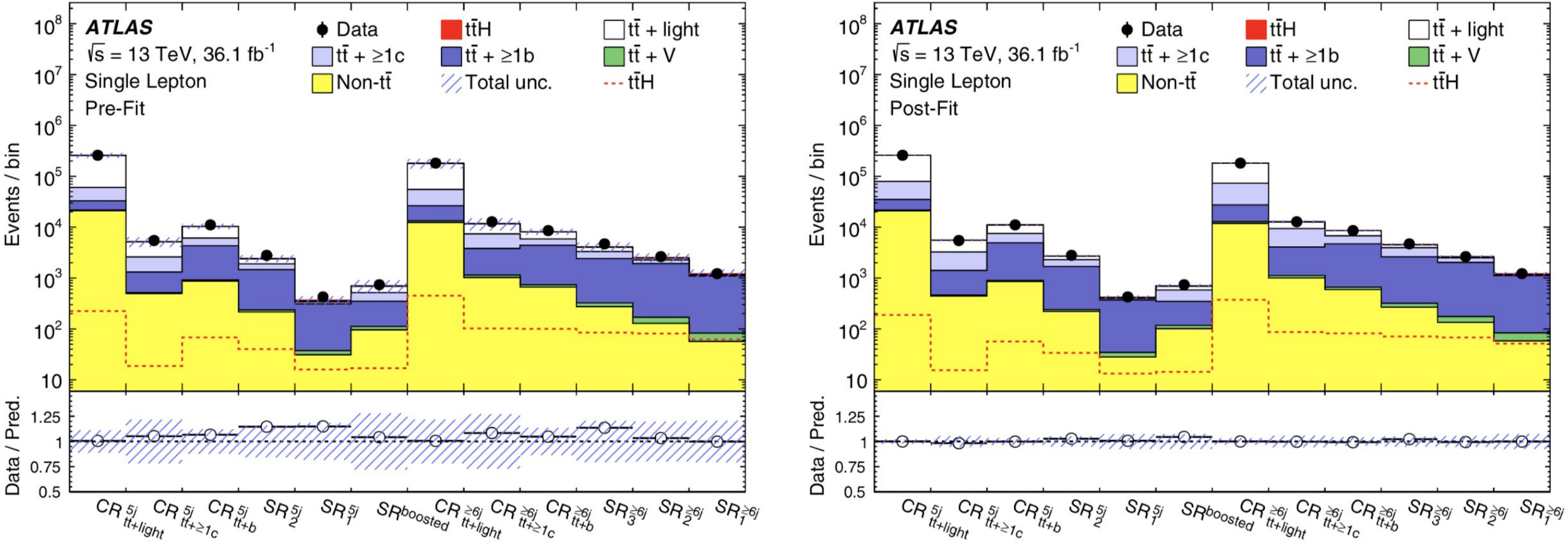
Training inputs



- Two stage BDT for event reconstruction (match jets to H or t decays) and classification (signal vs background) (in total 9 SRs and 10 CRs)

$t\bar{t}H$ ($H \rightarrow b\bar{b}$) fit

- Combined profile likelihood fit to all 19 regions is performed
  - Control background and systematic uncertainties
  - → Reduce uncertainties



- Obtain signal strength $\mu = \sigma_{\text{measured}}/\sigma_{\text{SM}}$

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

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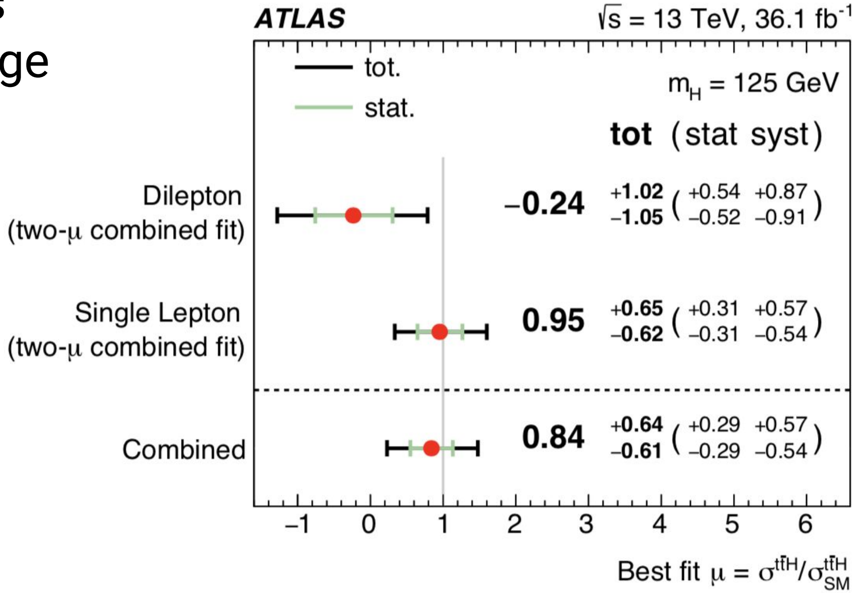
- Dominated by systematic uncertainties
- BKG MC stat. uncertainties are also large

Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modelling	+0.46	−0.46
Background model statistics	+0.29	−0.31
Jet flavour tagging	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modelling	+0.22	−0.05
$t\bar{t} + \geq 1c$ modelling	+0.09	−0.11
Jet-vertex association, pileup modelling	+0.03	−0.05
Other background modelling	+0.08	−0.08
$t\bar{t}$ + light modelling	+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
$t\bar{t} + \geq 1b$ normalisation	+0.09	−0.10
$t\bar{t} + \geq 1c$ normalisation	+0.02	−0.03
Statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61

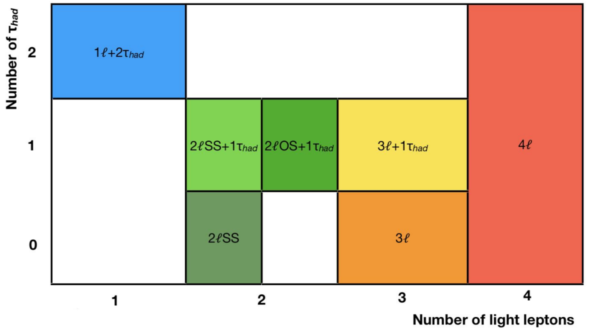


→ Observed significance: 1.4 σ (1.6 σ expected)

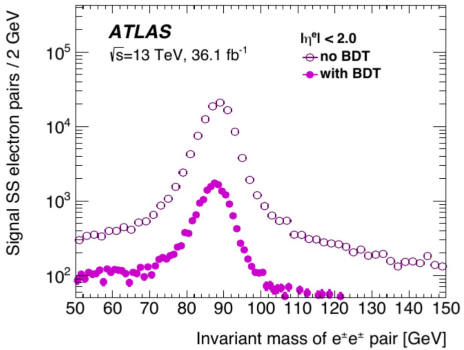
$t\bar{t}H$ (multilepton) analysis with 2015+2016 data

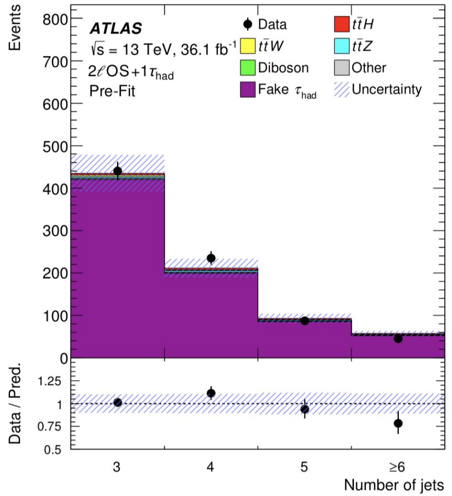
- $H \to W^+W^-/ZZ^*/\tau\bar{\tau}$ & $t\bar{t} \to 1\ell/2\ell$

- 7 channels depending on # leptons and # τ_{had}
- Split in 8 SRs & 4 CRs

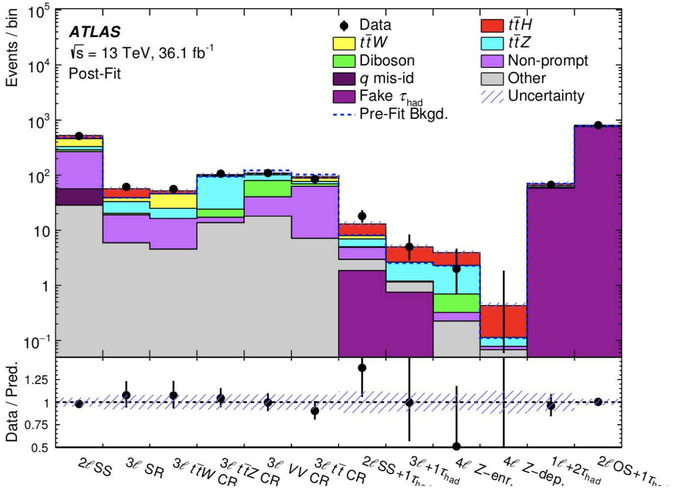


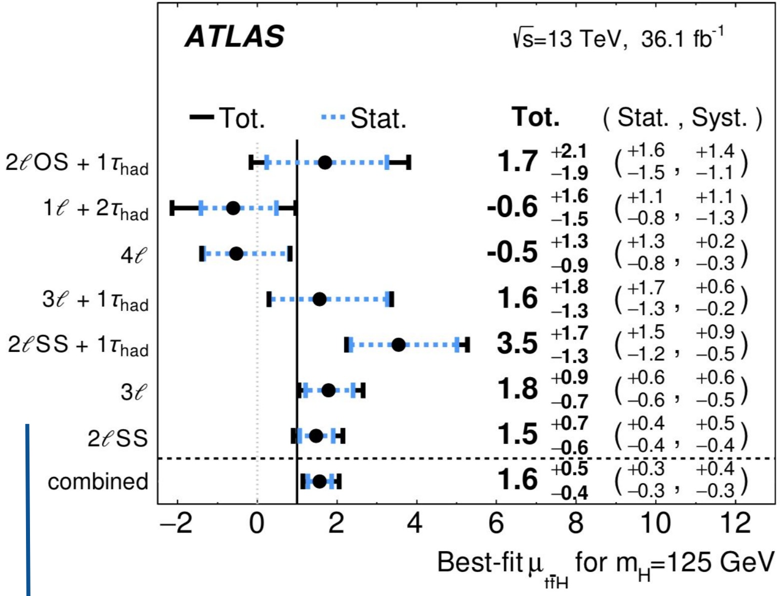
- Main analysis challenge: reducible backgrounds: $t\bar{t}\gamma$, $t\bar{t}Z$
- Misidentification of e charge reduced with dedicated BDT
- Non-prompt e or μ reduced with dedicated BDT
- Fake τ_{had} significant background in τ channels
- Prompt e or μ estimated from MC





- Profile likelihood fit of the 12 regions
  - BDT discriminant used in 5 SRs,
  - total yield used in regions with low stats





- Total systematics ≈ statistical uncertainty (± 0.30)
- Main systematics: signal modelling, JES/JER

→ Significance: 4.1 σ (2.8 σ expected)

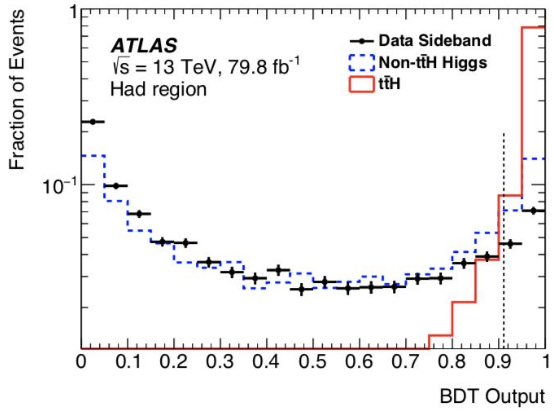
→ **Evidence for tt̄H production!**

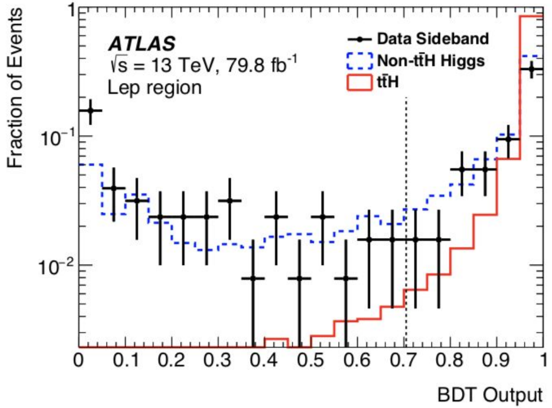
$t\bar{t}H$ ($H \rightarrow \gamma\gamma$) analysis with 2015-2017 data

- Channel used since Run-I (including 7 TeV)
- Sensitivity improved by ~50% compared to 2015+2016 data analysis (refined analysis strategy and updated reconstruction software)

- $H \rightarrow \gamma\gamma$ with 105 GeV < $m_{\gamma\gamma}$ < 160 GeV & ≥ 1 b-tagged jet
- Two SRs
  - Hadronic: ≥ 2 jets & 0 isolated ℓ (only e, μ)
  - Leptonic: ≥ 1 isolated ℓ (only e, μ)

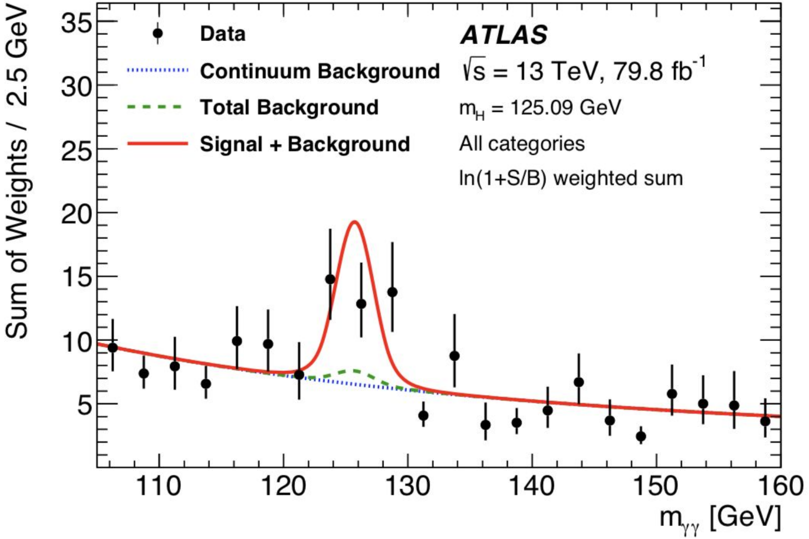
- Train BDT in each region with object-level variables





$t\bar{t}H$ ($H \rightarrow \gamma\gamma$) fit

- Categorize events depending on the value of the BDT response
  - 4 categories for the hadronic channel
  - 3 categories for the leptonic channel
  - → Optimize sensitivity to the $t\bar{t}H$ signal
- Global fit of diphoton mass is performed
  - Weighted $m_{\gamma\gamma}$ spectrum
- Main systematics
  - Signal modelling
  - γ isolation and energy scale & resolution
  - JES/JER



$t\bar{t}H$ ($H \to \gamma\gamma$) results

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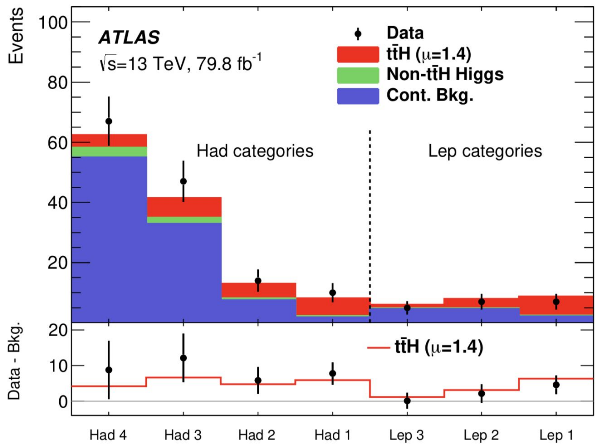
- Expected and observed event yields

Bin	Expected								Observed
	$t\bar{t}H$ (signal)		Non-$t\bar{t}H$ Higgs		Non-Higgs		Total		Total
$H \to \gamma\gamma$									
Had 1	4.2	± 1.1	0.49	± 0.33	1.8	± 0.5	6.4	± 1.3	10
Had 2	3.4	± 0.7	0.7	± 0.6	7.5	± 1.1	11.6	± 1.5	14
Had 3	4.7	± 0.9	2.0	± 1.7	32.9	± 2.2	39.6	± 3.2	47
Had 4	3.0	± 0.5	3.2	± 3.1	55.0	± 2.8	61	± 5	67
Lep 1	4.5	± 1.0	0.24	± 0.09	2.2	± 0.6	6.9	± 1.2	7
Lep 2	2.2	± 0.4	0.27	± 0.10	4.6	± 0.9	7.1	± 1.0	7
Lep 3	0.82	± 0.18	0.30	± 0.13	4.6	± 0.9	5.7	± 0.9	5



- $\mu = 1.4 \pm^{0.5}_{0.4} (\ ^{0.4}_{0.3}$ stat.)
- Combined significance: 4.1 σ (3.7 σ expected)
  - hadronic: 3.8 σ (2.7 σ exp.) - leptonic: 1.9 σ (2.5 σ exp.)

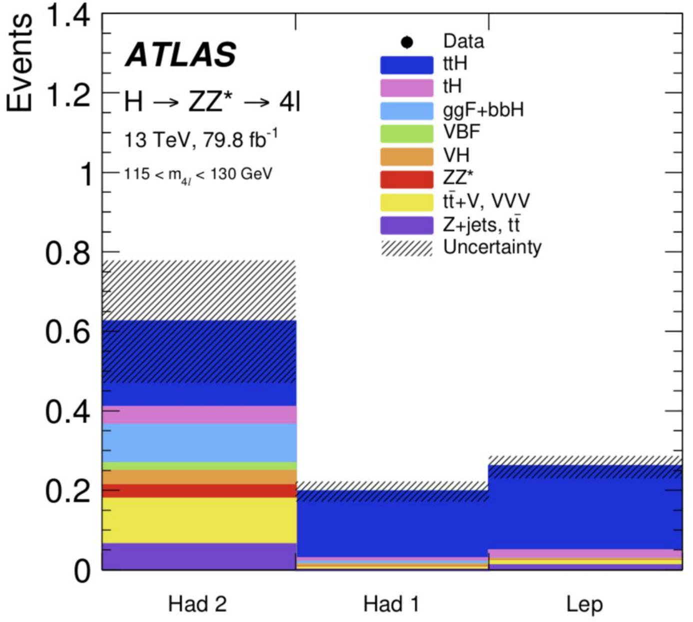
→ **Evidence for $t\bar{t}H$ production!**

$t\bar{t}H$ ($H \rightarrow ZZ^* \rightarrow 4\ell$) analysis with 2015-2017 data

- New channel with 13 TeV data

- $H \rightarrow 4e/4\mu/2e2\mu$, SFOS
- H candidate: 115 GeV < $m_{4\ell}$ < 130 GeV
- Two SRs enriched in $t\bar{t}H$
  - ≥ 1 *b*-tagged jet
  - Hadronic: ≥ 4 jets & leptonic: ≥ 1ℓ + ≥ 2 jets
  - Hadronic selection split in two subregions
    - BDT trained from 11 variables
    - 2 bins - highest one with higher S/B

- Expected significance: 1.2 σ
- No event observed → $\mu = \sigma_{measured}/\sigma_{SM} < 1.8$ @ 68% C.L.



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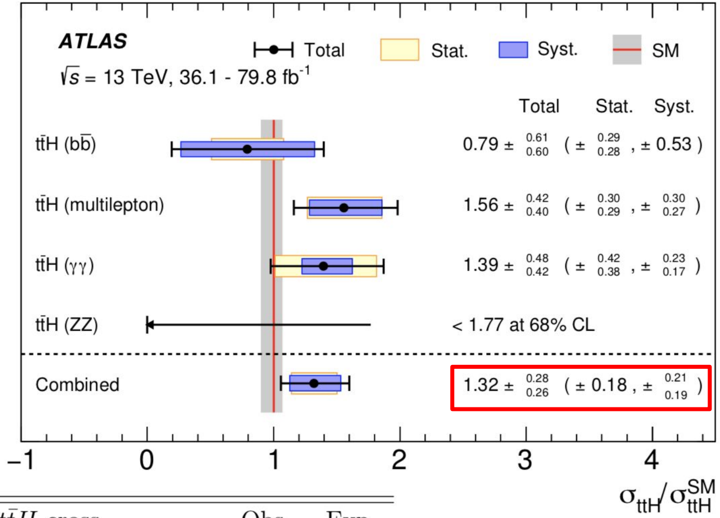
Combination

Combination 2015+2016(+2017) data

- **Observation (5.8 σ) with Run-II data**
  $\rightarrow \sigma_{obs}/\sigma_{SM} = 1.32 \pm^{0.28}_{0.26}$
- Improved significance when including Run-I
- Result compatible with SM predictions and constraints from indirect loop contributions



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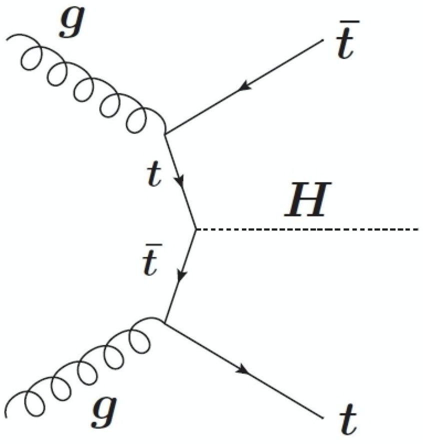
Analysis	Integrated luminosity [fb^{-1}]	$t\bar{t}H$ cross section [fb]	Obs. sign.	Exp. sign.
$H \rightarrow \gamma\gamma$	79.8	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)	4.1 σ	3.7 σ
$H \rightarrow$ multilepton	36.1	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)	4.1 σ	2.8 σ
$H \rightarrow b\bar{b}$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

Conclusions

- **Combination of different $t\bar{t}H$ decay channels necessary for a robust $t\bar{t}H$ measurement**
  - **The $t\bar{t}H$ production was observed!**
  - The top and the Higgs do interact!
  - Results in agreement with theory



Outlook

- Ongoing effort to improve uncertainties
  - More data, include 2017 data in all analyses (and 2018 data for full Run-II analyses)
  - Improving analysis techniques
  - Discussions in LHC Higgs cross-section working group with theorists and CMS

Thank you for your attention!