# “Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector”

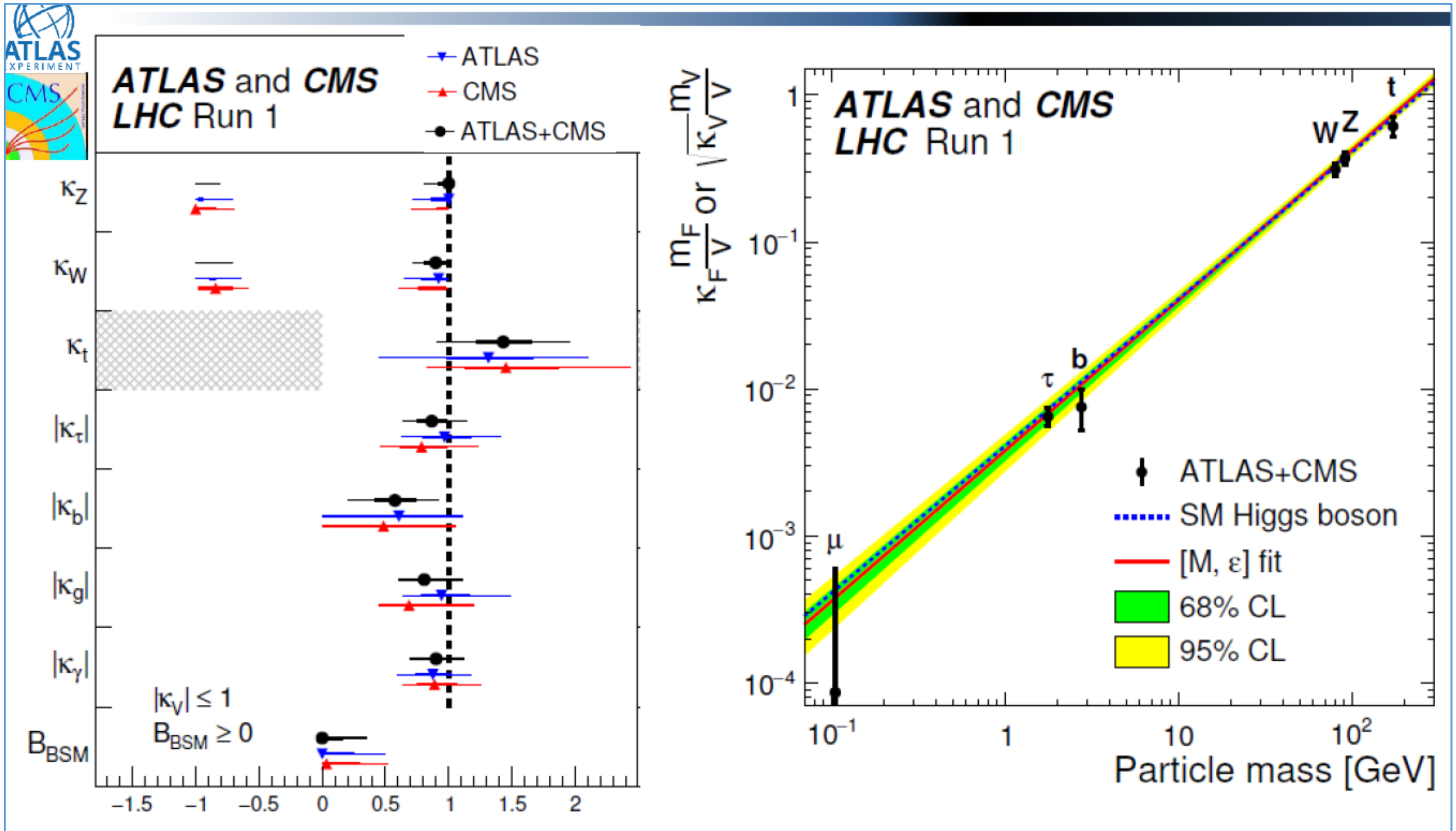
The ATLAS Collaboration

( from arXiv: 1806.00425v1 )

***JC72 07/20/2018***

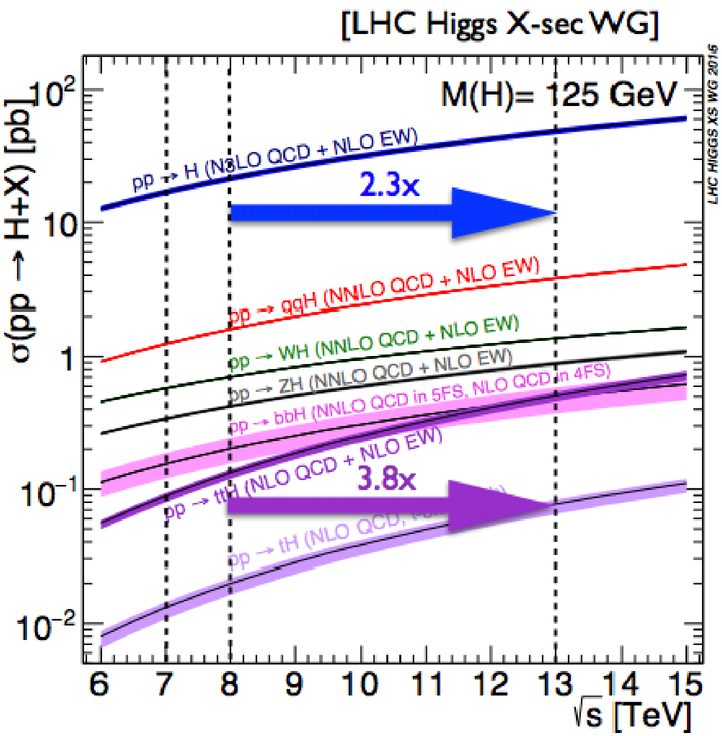
# Higgs couplings

Measurement of the Higgs couplings is something fundamental issue, to confirm whether Higgs boson give its “mass” entirely or not enough



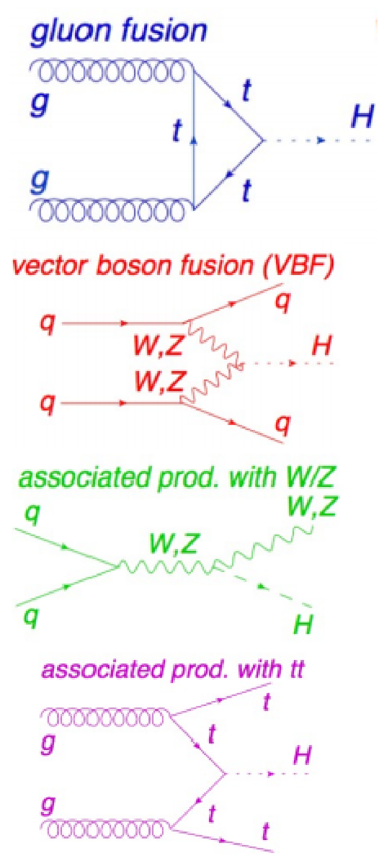

JHEP 08 (2016) 045

# Higgs Production




- Significant increase in production rate due to higher center-of-mass energy from LHC Run-1 to Run-2!

**Production modes**




**Higgs bosons produced in Run 2 (2015-2017)**

| Production mode | Higgs bosons produced in Run 2 (2015-2017) |
|---|---|
| gluon fusion | ~4M |
| vector boson fusion (VBF) | ~300k |
| associated prod. with W/Z | ~200k |
| associated prod. with tt | ~40k |

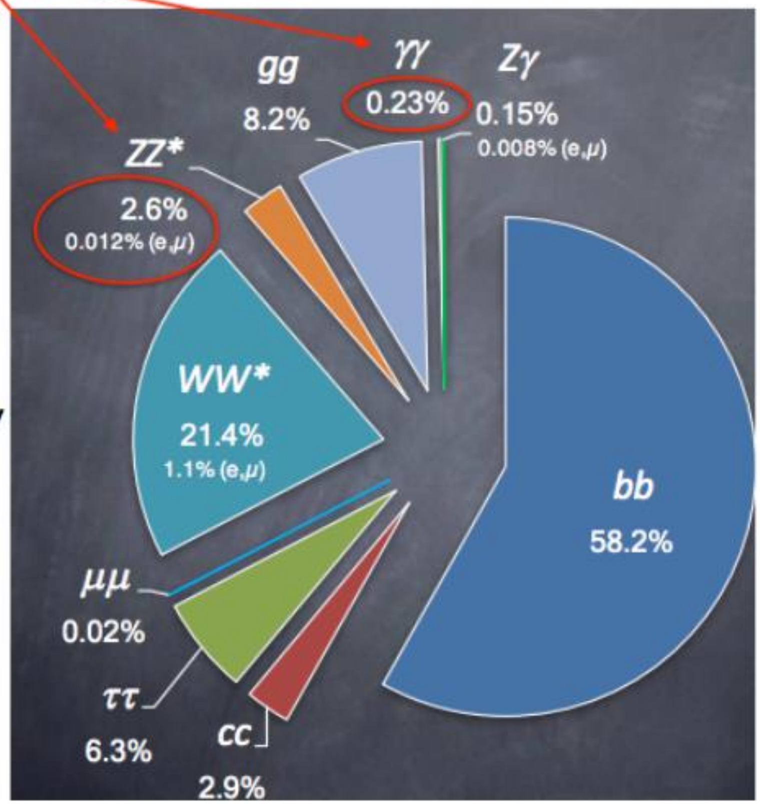


From the slide by Zhijun Liang

# Higgs Decay

- H→bb is the Dominant Decay mode of Higgs Boson(58%)

ZZ, γγ: high mass resolution channels mass and precise differential measurements




WW: High BR, but low mass resolution

μμ: very small BR, but access to coupling to 2nd generation fermions

bb, ττ: high BR, but low S/B, important to directly probe Higgs boson coupling to fermions



From the slide by Zhijun Liang

# ttH process

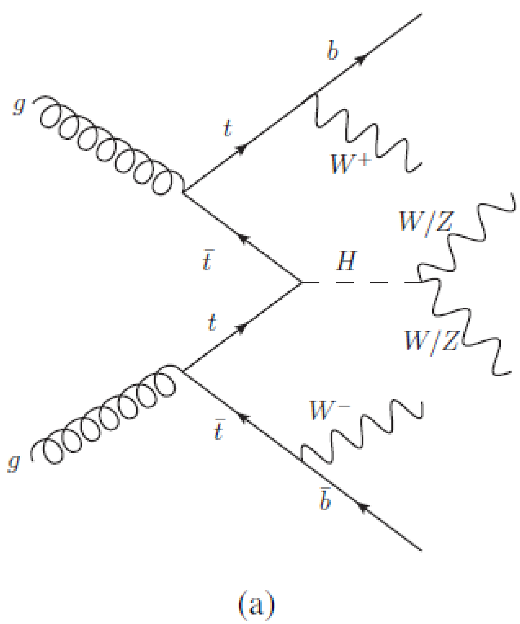



Figure 1: Examples of tree-level Feynman diagrams for the production of the Higgs boson in association with a pair of top quarks. Higgs boson decays to (left) $WW/ZZ$ or (right) $\tau\tau$ are shown.

Final state contains
"bbWW" from tt and "WW/ZZ/ττ (in this fig)" from Higgs

From arXiv:1712.08891v2 (or PRD 97 (2018) 072003 )
“Evidence for the associated production of the Higgs boson and a top quark pair with the ATLAS detector”

( published 9 April 2018 )

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- Using 36.1 $fb^{-1}$ pp data at 13 TeV

- from Higgs->(WW* or $\tau\tau$ ->)multilepton decays, the ttH signal significance is 4.1 standard deviation

- With combination of other Higgs boson decay modes, bb, $\gamma\gamma$, ZZ->4l, the significance is 4.2 standard deviation.

# “multilepton” channels ( Higgs -> multi lepton )

ttH -> tt(->bbWW) + H( -> WW* or -> ττ ) is targeted.

(maybe ..) H->bb channel has largest branching ratio, but difficult to distinguish the “b”s

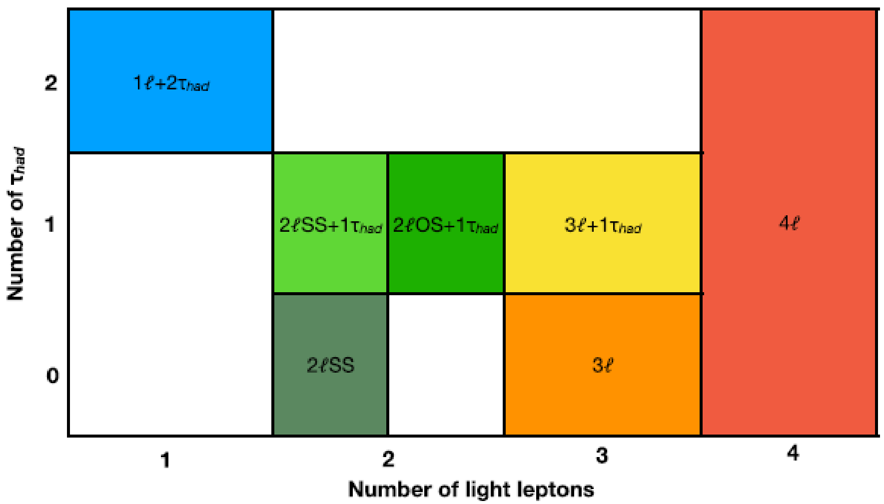



FIG. 3. The channels used in the analysis organized according to the number of selected light leptons and $\tau_{\mathrm{had}}$ candidates. The selection requirements for each channel are in Table III.

(i) two same-charge light leptons and no hadronically decaying $\tau$ lepton candidates ($2\ell$SS);
(ii) three light leptons and no hadronically decaying $\tau$ lepton candidates ($3\ell$);
(iii) four light leptons ($4\ell$);
(iv) one light lepton and two opposite-charge hadronically decaying $\tau$ lepton candidates ($1\ell + 2\tau_{\mathrm{had}}$);
(v) two same-charge light leptons and one hadronically decaying $\tau$ lepton candidate ($2\ell\mathrm{SS} + 1\tau_{\mathrm{had}}$);
(vi) two opposite-charge light leptons and one hadronically decaying $\tau$ lepton candidate ($2\ell\mathrm{OS} + 1\tau_{\mathrm{had}}$);
(vii) three light leptons and one hadronically decaying $\tau$ lepton candidate ($3\ell + 1\tau_{\mathrm{had}}$).

# Combination

Table 14: Summary of the observed and expected $\mu$ measurements and $t\bar{t}H$ production significance from individual analyses and the combination. As no events are observed in the $H \to 4\ell$ analysis, a 68% confidence level (CL) upper limit on $\mu$, computed using the $\mathrm{CL_s}$ method [108], is reported.

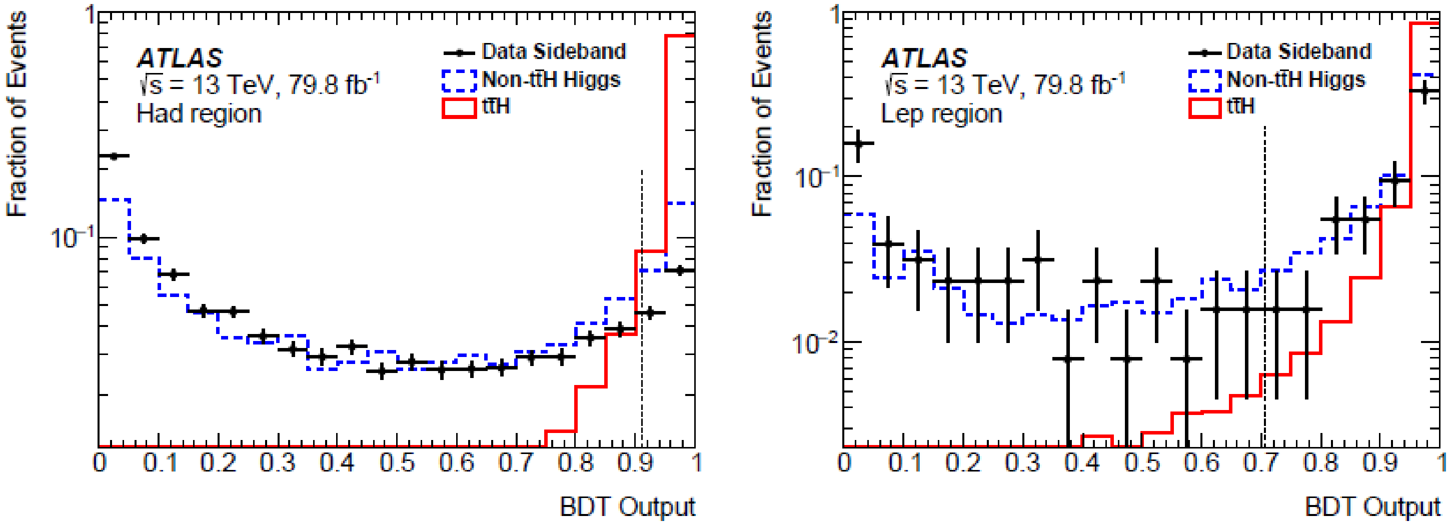
| Channel | Best-fit $\mu$ | | Significance | |
|---|---|---|---|---|
| | Observed | Expected | Observed | Expected |
| Multilepton | $1.6^{+0.5}_{-0.4}$ | $1.0^{+0.4}_{-0.4}$ | $4.1\sigma$ | $2.8\sigma$ |
| $H \to b\bar{b}$ | $0.8^{+0.6}_{-0.6}$ | $1.0^{+0.6}_{-0.6}$ | $1.4\sigma$ | $1.6\sigma$ |
| $H \to \gamma\gamma$ | $0.6^{+0.7}_{-0.6}$ | $1.0^{+0.8}_{-0.6}$ | $0.9\sigma$ | $1.7\sigma$ |
| $H \to 4\ell$ | $< 1.9$ | $1.0^{+3.2}_{-1.0}$ | — | $0.6\sigma$ |
| Combined | $1.2^{+0.3}_{-0.3}$ | $1.0^{+0.3}_{-0.3}$ | $4.2\sigma$ | $3.8\sigma$ |

let’s back to the paper for JC72

# Condition

- Using 79.8 $fb^{-1}$ pp data at 13 TeV
- the analysis of H->gg , H->ZZ*->4l is updated
- combination with H->bb, and WW* $\tau\tau$ -> multilepton

# BDT distribution for H->γγ analysis



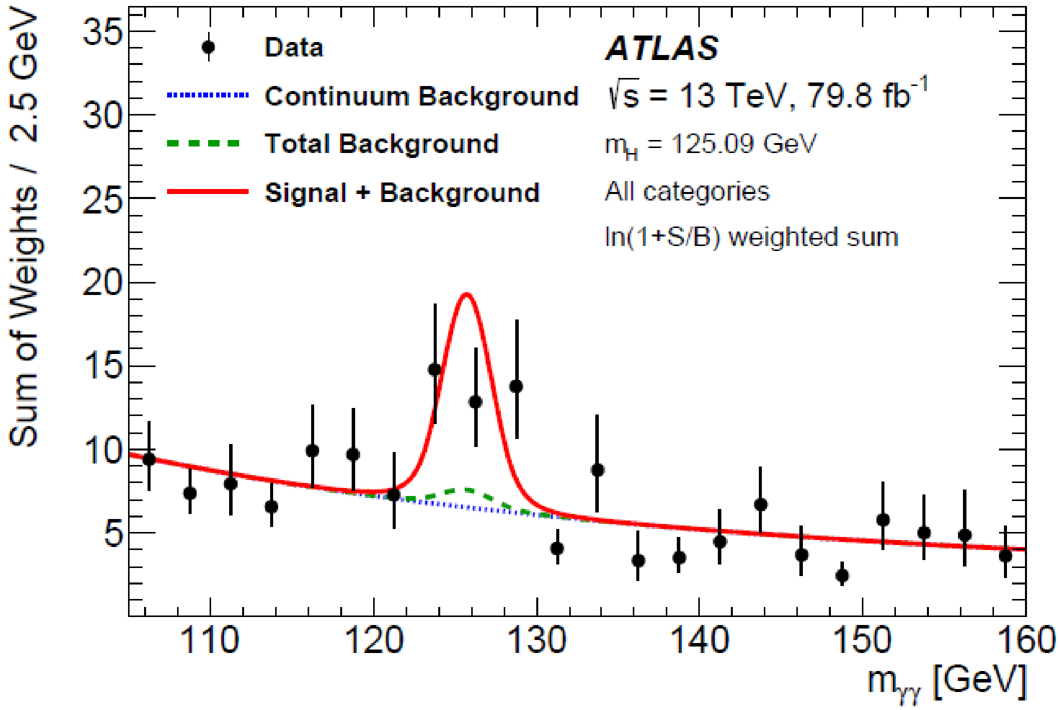

(a) (b)

Figure 1: Distribution of the BDT output in the (a) Had and (b) Lep region in the $H \to \gamma\gamma$ analysis. The distribution of the simulated $t\bar{t}H$ signal is compared with that of the other Higgs boson production modes, as well as to the continuum background from data in the diphoton invariant-mass sidebands of 105 GeV $< m_{\gamma\gamma} <$ 120 GeV and 130 GeV $< m_{\gamma\gamma} <$ 160 GeV. Events to the left of the vertical line are rejected. The distributions are normalized to unity.

Input : P4(photon, jets, leptons) , b-tagging information of jets

“Events are categorized into four (three) bins in the Had(Lep) region depending on the value of the BDT response.” --> Maybe, they are combined at the final.

# diphoton invariant mass spectrum in the ttH analysis




*4.1 standard deviation from H->$\gamma\gamma$ channel*

# Combination

Table 3: Measured total $t\bar{t}H$ production cross sections at 13 TeV, as well as observed (Obs.) and expected (Exp.) significances (sign.) relative to the background-only hypothesis. The results of the individual analyses, as well as the combined results are shown. Since no event is observed in the $H \to ZZ^* \to 4\ell$ decay channel, an observed upper limit is set at 68% confidence level on the $t\bar{t}H$ production cross section in that channel using pseudo-experiments.

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

# I have omitted an explanation about H->ZZ*->4l channel reported in the paper

finally, the significance reaches 5 sigma

# Systematic Uncertainty

Table 2: Summary of the systematic uncertainties affecting the combined $t\bar{t}H$ cross-section measurement at 13 TeV. Only systematic uncertainty sources with at least 1% impact are listed. The fake-lepton uncertainty is due to the estimate of leptons from heavy-flavour decay, conversions or misidentified hadronic jets. The jet, electron, and photon uncertainties, as well as the uncertainties associated with hadronically decaying $\tau$-leptons, include those in reconstruction and identification efficiencies, as well as in the energy scale and resolution. The Monte Carlo (MC) statistical uncertainty is due to limited numbers of simulated events. More detailed descriptions of the sources of the systematic uncertainties are given in Refs. [10, 15].

| 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 |
| $\tau$-lepton | 2.5 |
| Flavour tagging | 1.8 |
| MC statistical uncertainties | 4.4 |

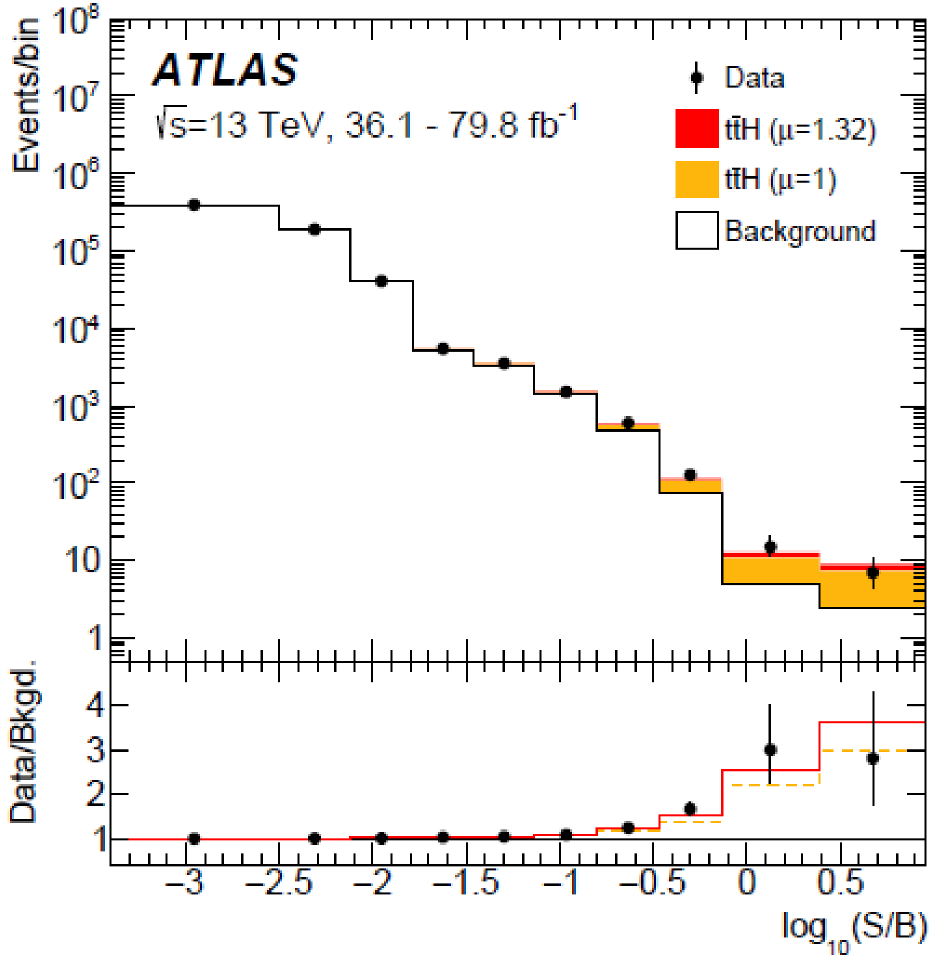



Figure 4: Observed event yields in all analysis categories in up to 79.8 fb$^{-1}$ of 13 TeV data. The background yields correspond to the observed fit results, and the signal yields are shown for both the observed results ($\mu$ = 1.32) and the SM prediction ($\mu$ = 1). The discriminant bins in all categories are ranked by $\log_{10}(S/B)$, where $S$ is the signal yield and $B$ the background yield extracted from the fit with freely floating signal, and combined such that $\log_{10}(S + B)$ decreases approximately linearly. For the $H \to \gamma\gamma$ analysis, only events in the smallest $m_{\gamma\gamma}$ window containing 90% of the expected signal are considered. The lower panel shows the ratio of the data to the background estimated from the fit with freely floating signal, compared to the expected distribution including the signal assuming $\mu$ = 1.32 (full red) and $\mu$ = 1 (dashed yellow). The error bars on the data are statistical.

# Signal Strength

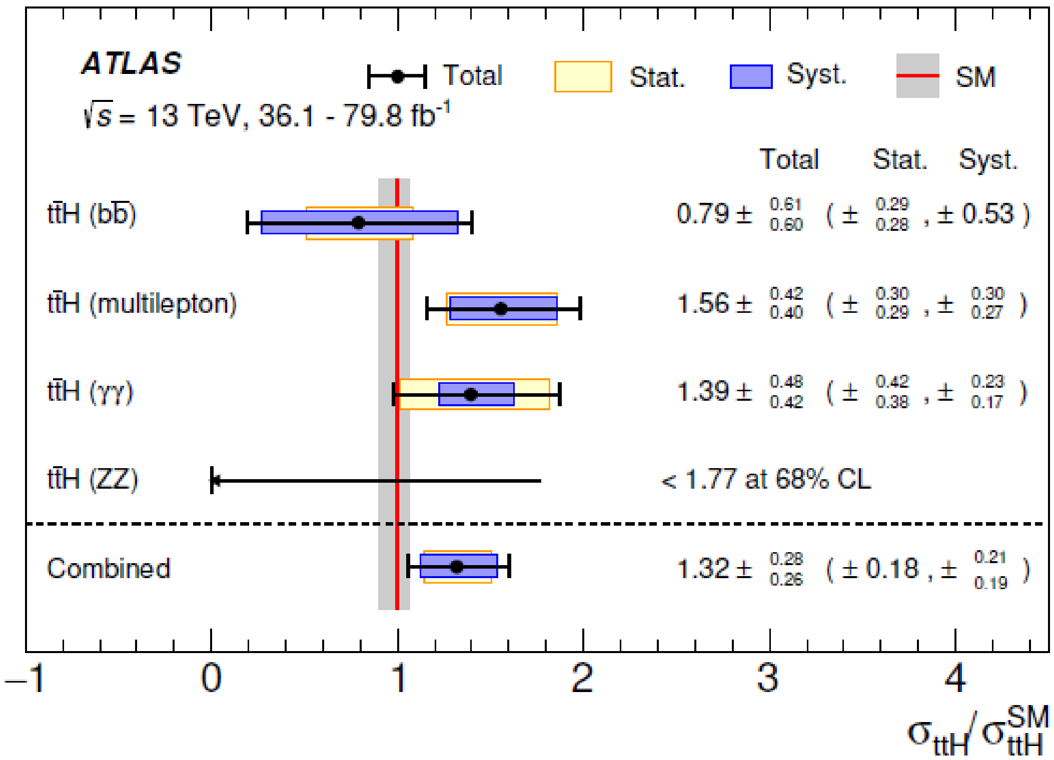
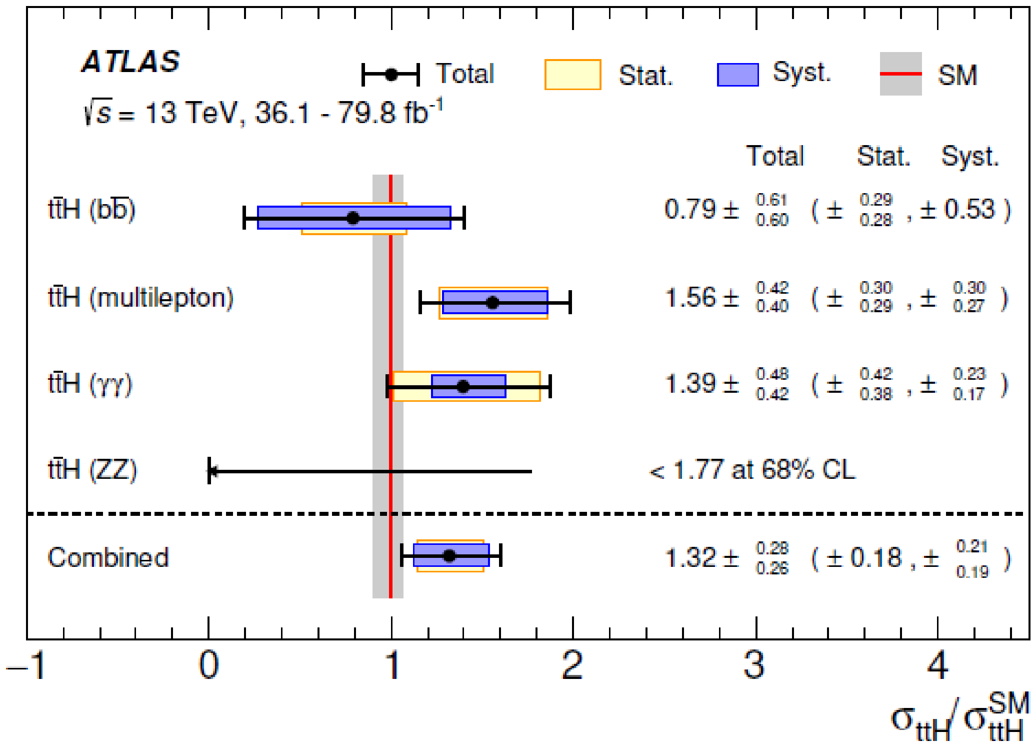



Figure 5: Combined $t\bar{t}H$ production cross section, as well as cross sections measured in the individual analyses, divided by the SM prediction. The $\gamma\gamma$ and $ZZ^* \to 4\ell$ analyses use 13 TeV data corresponding to an integrated luminosity of 79.8 fb$^{-1}$, and the multilepton and $b\bar{b}$ analyses use data corresponding to an integrated luminosity of 36.1 fb$^{-1}$. The black lines show the total uncertainties, and the bands indicate the statistical and systematic uncertainties. The red vertical line indicates the SM cross-section prediction [37], and the grey band represents the PDF+$\alpha_S$ uncertainties and the uncertainties due to missing higher-order corrections.

# Cross Section - I.

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# Cross Section - II.

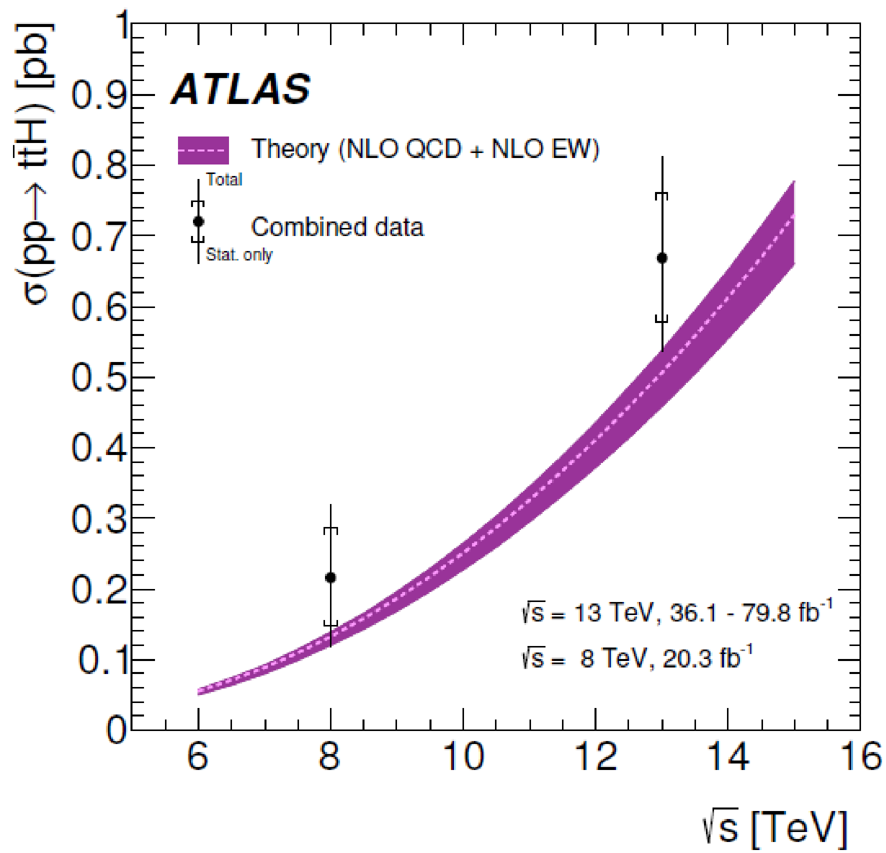


Figure 6: Measured $t\bar{t}H$ cross sections in $pp$ collisions at centre-of-mass energies of 8 TeV and 13 TeV. Both the total and statistical-only uncertainties are shown. The measurements are compared with the SM prediction [37]. The band around the prediction represents the PDF+$\alpha_S$ uncertainties and the uncertainties due to missing higher-order corrections.

# Summary

・From ATLAS, the production of the Higgs boson in association with top quark pairs is observed with a significance of 6.3 standard deviations

・The cross section measured is

$$670 \pm 90(\text{stat.}) \pm 110/100\ (\text{syst.})\ \ \text{fb}$$

in agreement with the SM prediction.