

**University of  
Zurich<sup>UZH</sup>**

# Observation of $t\bar{t}H$ production in CMS

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Daniel Salerno  
on behalf of the CMS Collaboration

Blois 2018 – 30th Rencontres de Blois  
*6 June 2018, Château de Blois, France*

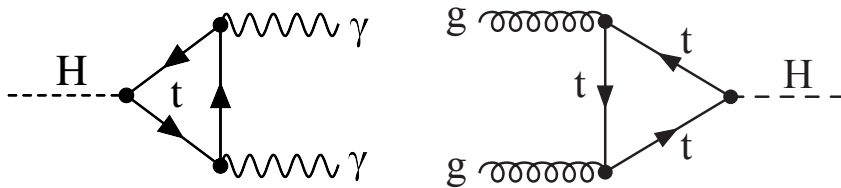
# ttH production

CERN-2017-002-M

LHC Higgs Cross Section WG Report 4

## Motivation

- Provides a **direct probe** of the important top–Higgs coupling
  - ▶ Yukawa coupling  $y_t \sim 1$
  - ▶ Indirect loop measurements can be influenced by BSM physics

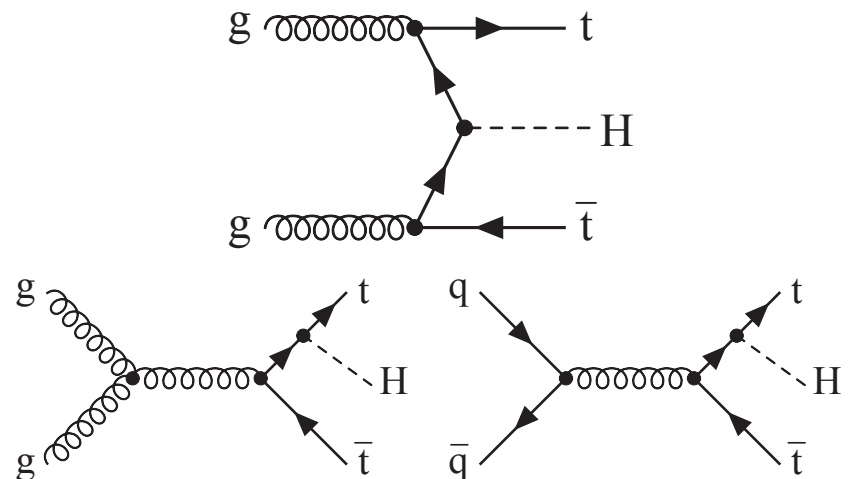


- First measurement of Higgs coupling to up-type fermion
- Non-SM ttH rate could indicate presence of new physics

## Properties

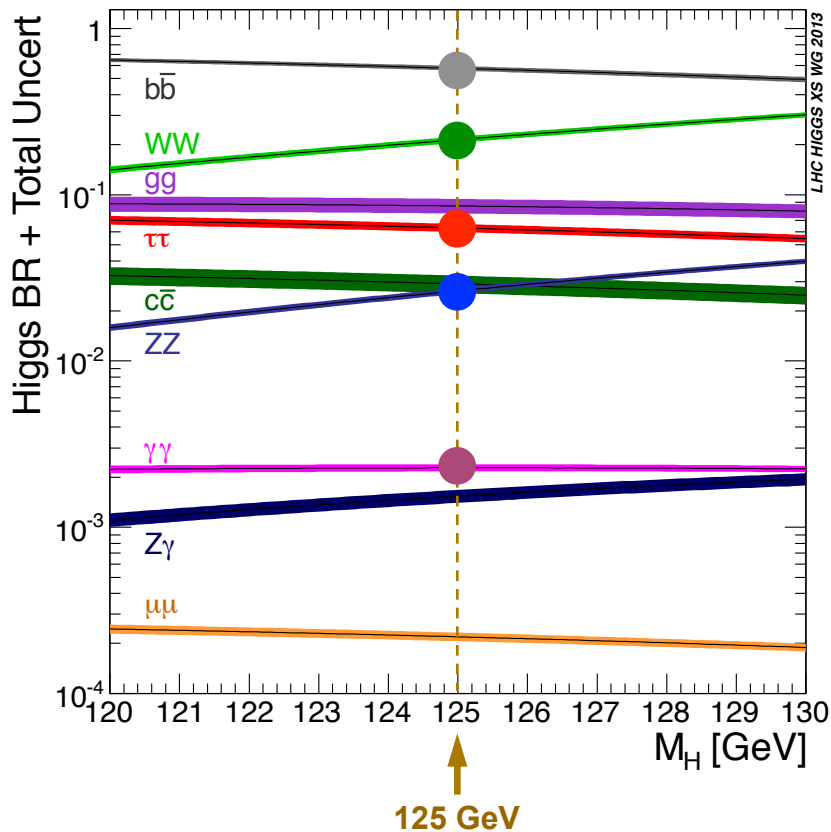
- Xsec: 0.5071 pb +6.8/−9.9%
  - ▶ NLO QCD and NLO EW accuracy
- **Expect ~18,000 SM ttH events** in 2016 data at CMS
  - ▶  $\sim 36 \text{ fb}^{-1}$

### LO Feynman diagrams:



# Higgs boson decay

## Comments



## Decay branching ratios

- $H \rightarrow b\bar{b}$  has the largest branching ratio  $\sim 45\%$ 
  - ▶ Large background
- $H \rightarrow ZZ (\rightarrow 4\ell)$  provides a very clean signature with few background events
  - ▶ Small branching ratio  $\sim 2\%$
- $H \rightarrow \gamma\gamma$  has a clean signature on top of a well understood background

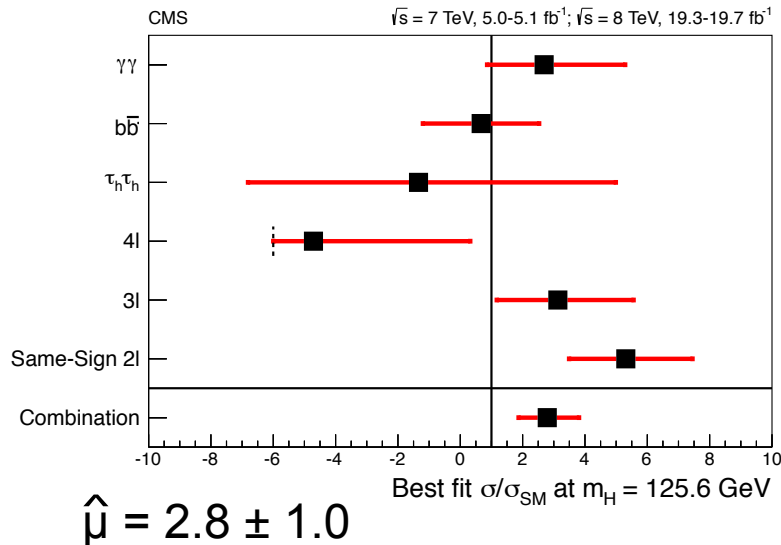
## Decay channels analysed

**Fermions:**  $H \rightarrow b\bar{b}$      $H \rightarrow \tau\tau$   
**Bosons:**     $H \rightarrow WW$      $H \rightarrow ZZ$      $H \rightarrow \gamma\gamma$

# Contributing analyses

## 7+8 TeV (up to 5.1 fb<sup>-1</sup> + 19.7 fb<sup>-1</sup>)

- ttH → multileptons
- ttH → bb (leptonic)
- H → γγ
  - ▶ HIG-13-029 JHEP 09 (2014) 087



## 13 TeV (35.9 fb<sup>-1</sup>)

- ttH → multileptons
  - ▶ HIG-17-018 arXiv:1803.05485
- ttH → bb (hadronic)
  - ▶ HIG-17-022 arXiv:1803.06986
- ttH → bb (leptonic)
  - ▶ HIG-17-026 arXiv:1804.03682
- H → ZZ → 4l
  - ▶ HIG-16-041 JHEP 11 (2017) 047
- H → γγ
  - ▶ HIG-16-040 arXiv:1804.02716
- Data collected in 2016

# ttH, multileptons

CMS-HIG-17-018  
arXiv:1803.05485

## Analysis overview

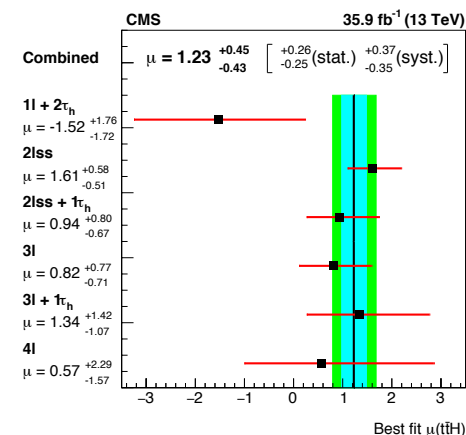
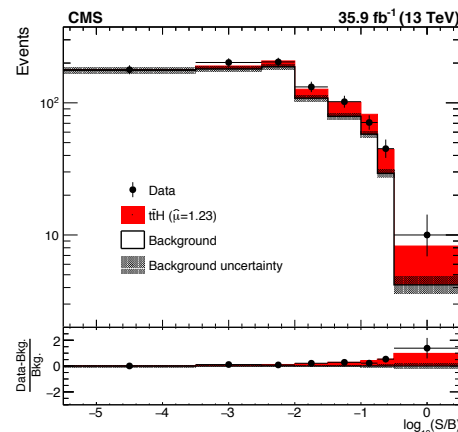
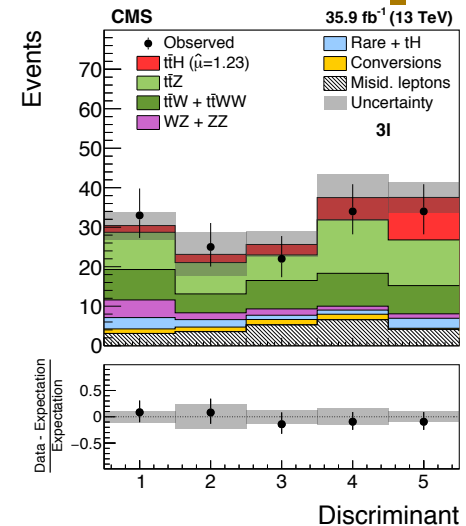
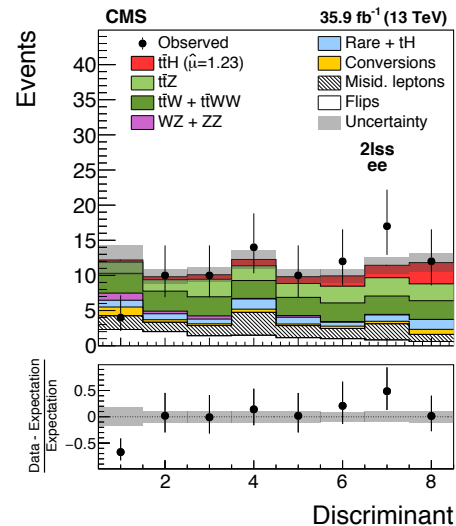
- 3 channels:  $H \rightarrow ZZ^*, WW^*, \tau\tau$ 
  - 6 categories based on lepton ( $e/\mu$ ) and hadronic tau ( $\tau_h$ ) multiplicity
- "Fake  $e/\mu/\tau_h$ " and "sign-flip" backgrounds estimated from data
- BDT, MEM and S/B binned final discriminant
  - Based on two BDTs: vs. tt and ttV
    - 18 total input variables
- Main systematics:  $e/\mu$  efficiencies, lepton misidentification, simulated background normalisation

Results at 13 TeV:  $\longrightarrow$

Obs. (Exp.) limit: 2.1 (0.8) x SM

Best fit  $\mu = \sigma/\sigma_{SM} = 1.23 \pm 0.44$

3.2 sigma significance



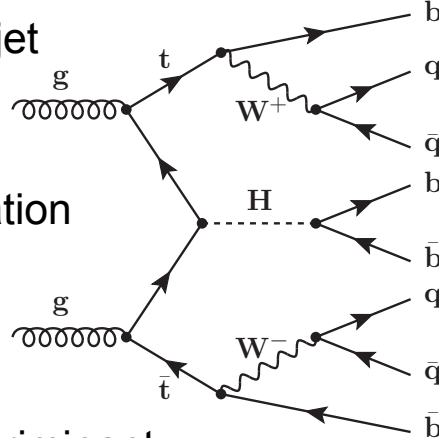


# ttH, H → bb (hadronic)

CMS-HIG-17-022  
arXiv:1803.06986

## Analysis overview

- All-jet triggers
- Data-driven QCD multijet estimation
  - 2 b-tag control region
- Quark-gluon discrimination
  - Early rejection of QCD
- 6 categories
  - Jet and b-jet multiplicity
- MEM used as final discriminant
- Main systematics: b-tagging, QCD normalisation and modelling

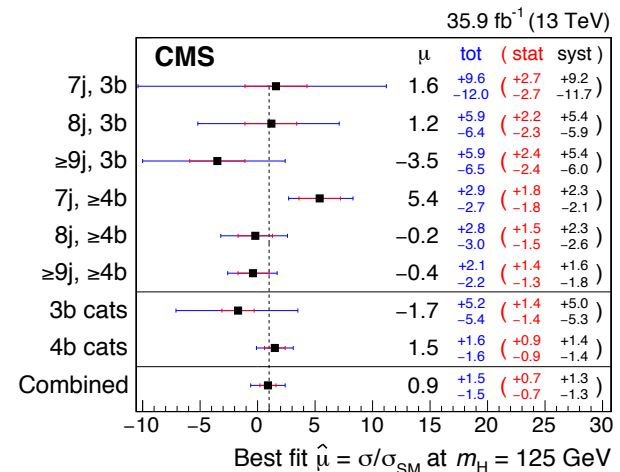
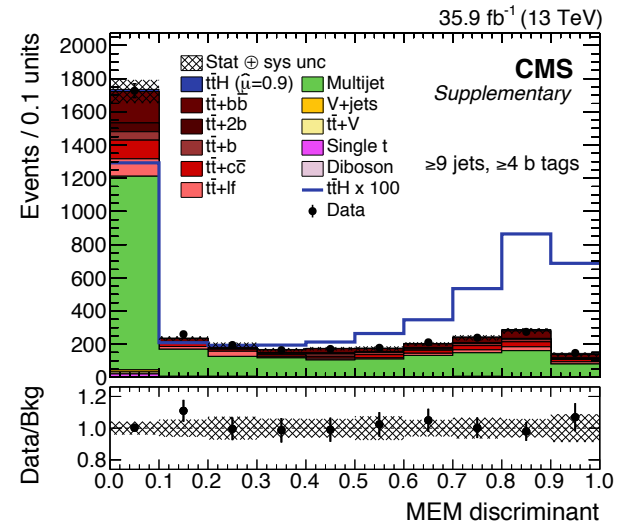


Results at 13 TeV:

Obs. (Exp.) limit: 3.8 (3.1) x SM

Best fit  $\mu = \sigma/\sigma_{SM} = 0.9 \pm 1.5$

0.6 sigma significance

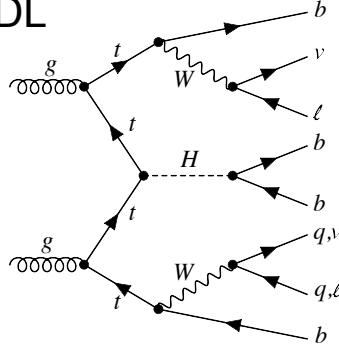


# ttH, H → bb (leptonic)

CMS-HIG-17-026  
arXiv:1804.03682

## Analysis overview

- 2 channels: SL and DL
  - e / μ triggers
- BDT, MEM, and DNN discriminants
- 5 main categories
  - jet / b-jet multiplicity
  - 21 final categories based on DNN class. (SL) and BDT output (DL)
- Main systematics: b-tagging, limited MC statistics, tt+hf normalisation and modelling

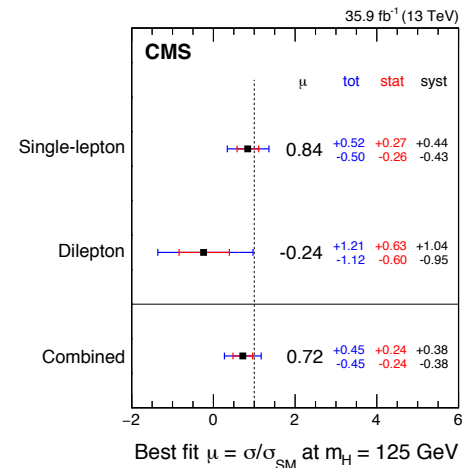
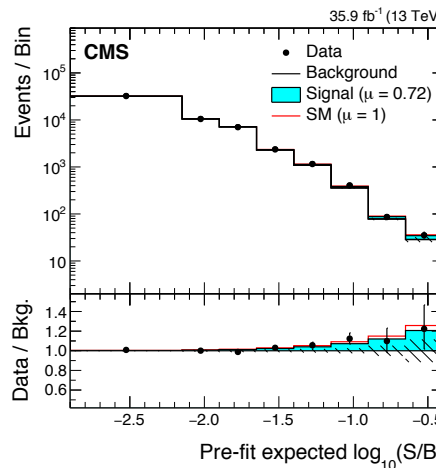
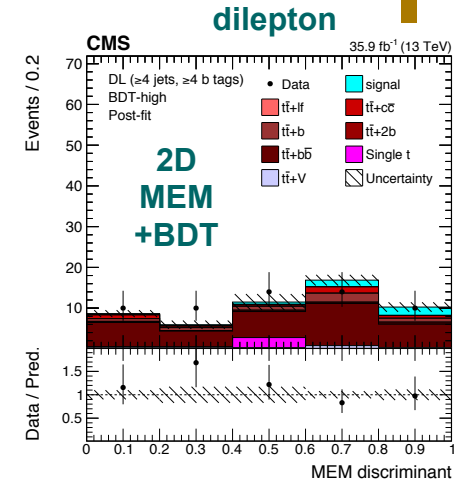
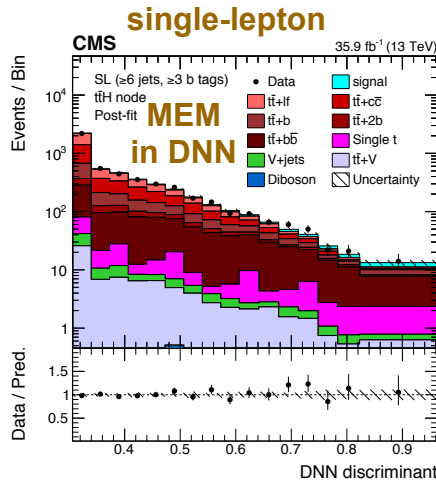


Results at 13 TeV:

Obs. (Exp.) limit: 1.51 (0.92) x SM

Best fit  $\mu = \sigma/\sigma_{SM} = 0.72 \pm 0.45$

1.6 sigma significance



# H → ZZ → 4ℓ (ttH cat.)

CMS-HIG-16-041  
arXiv:1706.09936

JHEP 11 (2017) 047

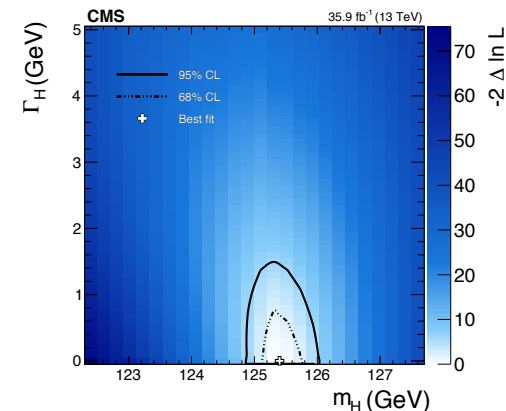
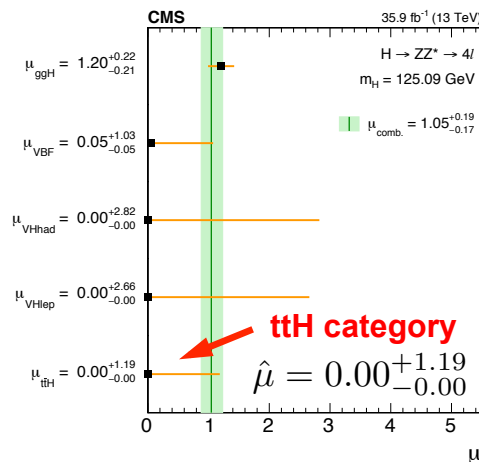
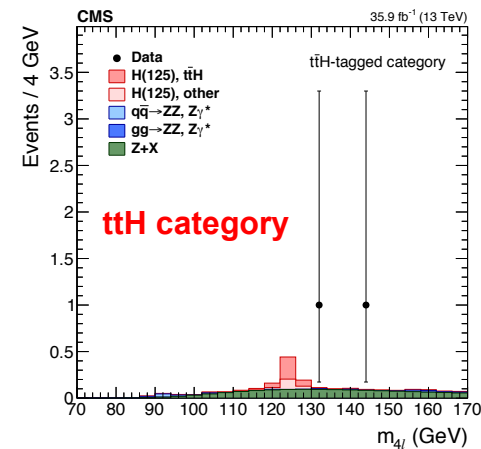
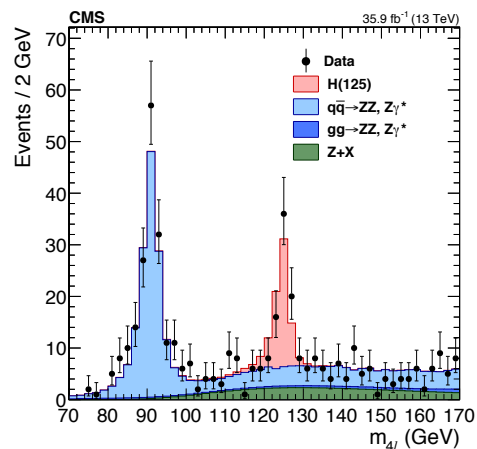
## Analysis overview

- Baseline H → ZZ selection:
  - ▶ 4e, 4μ, 2e2μ (opposite sign pairs)
    - 12,40 < m<sub>ℓℓ</sub> < 120 GeV
    - m<sub>4ℓ</sub> > 70 GeV
- Plus, either: ≥4 jets and ≥1 b-jet, or ≥1 additional lepton
- ZZ background from simulation, Z+jets from data
- Main systematics: e/μ efficiencies, theoretical uncertainties on ggH prediction

Inclusive results at 13 TeV: →

Best fit  $\mu = \sigma/\sigma_{SM} = 1.05 \pm 0.18$

$m_H = 125.26 \pm 0.22$  GeV,  $\Gamma_H < 1.10$  GeV





# H → γγ (ttH cat.)

CMS-HIG-16-040  
arXiv:1804.02716

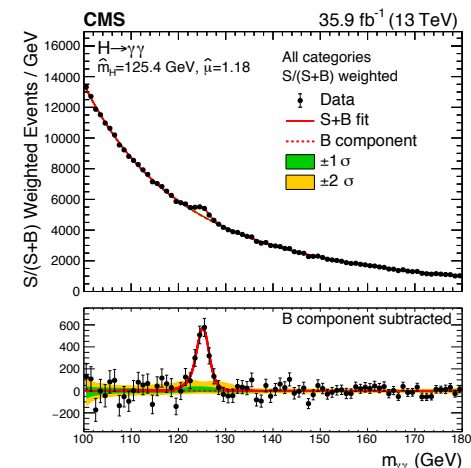
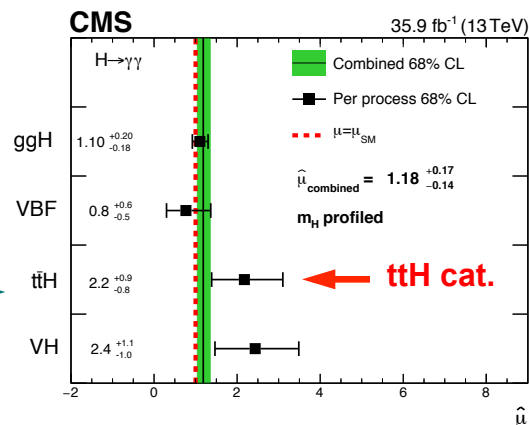
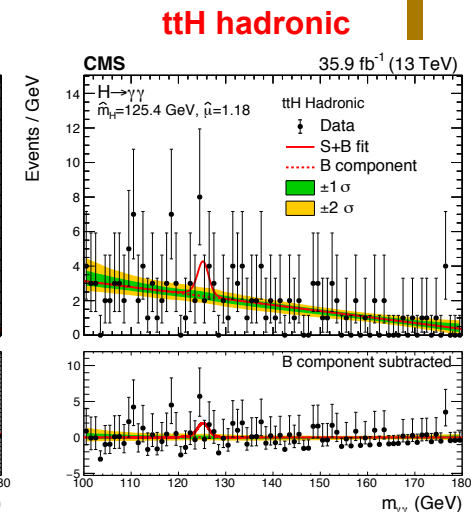
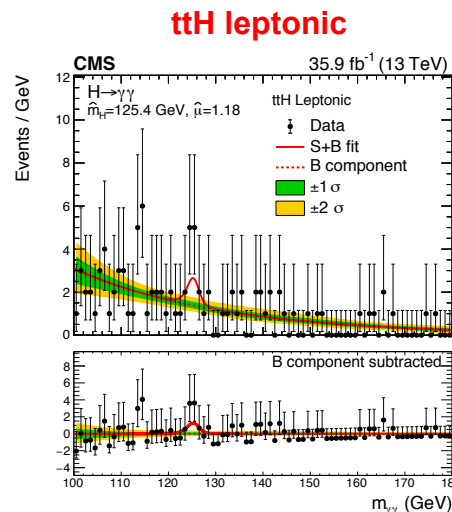
## Analysis overview

- Baseline H → γγ selection:
  - ▶ 2γ (identification & isolation criteria)
    - 100 < m<sub>γγ</sub> < 180 GeV
    - p<sub>T1</sub> > m<sub>γγ</sub>/3 and p<sub>T2</sub> > m<sub>γγ</sub>/4
- Plus, either:
  - ▶ ≥1 e/μ, ≥2 jets, and ≥1 b-jet
  - ▶ 0 e/μ, ≥3 jets, ≥1 b-jet, and ttH BDT cut
- γγ background from data and then smooth function fitted
- Main systematics (ttH): renorm. and factorisation scales, photon ID and energy scale

ttH results at 13 TeV:

Best fit  $\mu = \sigma/\sigma_{SM} = 2.2 \pm 0.9$

ttH significance: 3.3 sigma



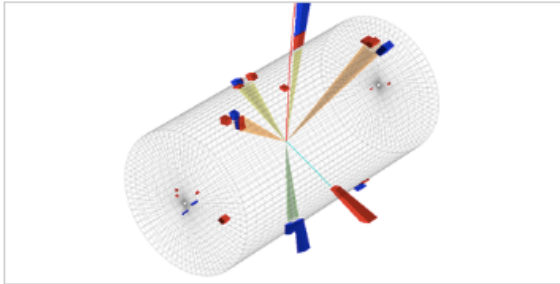
# ttH combination

CMS-HIG-17-035  
arXiv:1804.02610

PRL 120 (2018) 231801

APS  
physics

Physics ▾



PARTICLES AND FIELDS

Viewpoint: Sizing Up the Top Quark's Interaction with the Higgs

June 4, 2018

A proton collision experiment at CERN provides a new handle on the Higgs boson's interaction with the heaviest of the quarks. [Read More »](#)

## Systematic uncertainties

- All analysis specific uncertainties considered
- Systematic uncertainties from the same sources in 13 TeV and 7/8 TeV data are correlated
- Few correlations between Run 1 and 13 TeV
  - ▶ Signal and some background theory uncertainties
  - ▶ Experimental uncertainties largely uncorrelated

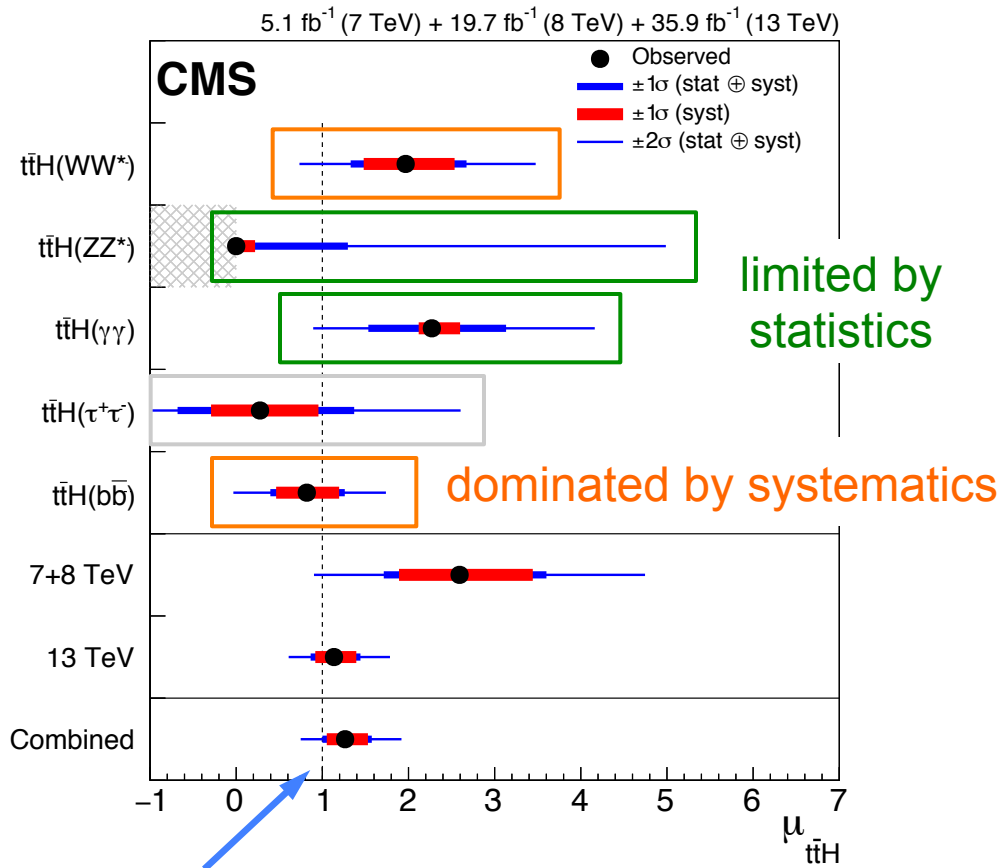
## Higgs processes

- Small contamination from other Higgs processes
  - ▶ e.g. ggH, VH, tH
  - ▶ Treated as backgrounds, normalised to SM prediction
  - ▶ Subject to standard theoretical uncertainties
- Assume SM branching ratios throughout
  - ▶ With uncertainties

# ttH combination

CMS-HIG-17-035  
arXiv:1804.02610

PRL 120 (2018) 231801



Parameter	Best fit	Stat	Uncertainty		
			Expt	Thbkd	Thsig
$\mu_{\text{ttH}}^{\text{WW}^*}$	1.97 <sup>+0.71</sup> <sub>-0.64</sub> (+0.57) (-0.54)	+0.42 -0.41	+0.46 -0.42 (+0.36) (-0.34)	+0.21 -0.21 (+0.17) (-0.17)	+0.25 -0.12 (+0.12) (-0.03)
$\mu_{\text{ttH}}^{\text{ZZ}^*}$	0.00 <sup>+1.30</sup> <sub>-0.00</sub> (+2.89) (-0.99)	+1.28 -0.00 (+2.82) (-0.99)	+0.20 -0.00 (+0.51) (-0.00)	+0.04 -0.00 (+0.15) (-0.00)	+0.09 -0.00 (+0.27) (-0.00)
$\mu_{\text{ttH}}^{\gamma\gamma}$	2.27 <sup>+0.86</sup> <sub>-0.74</sub> (+0.73) (-0.64)	+0.80 -0.72 (+0.71) (-0.64)	+0.15 -0.09 (+0.09) (-0.04)	+0.02 -0.01 (+0.01) (-0.00)	+0.29 -0.13 (+0.13) (-0.05)
$\mu_{\text{ttH}}^{\tau^+\tau^-}$	0.28 <sup>+1.09</sup> <sub>-0.96</sub> (+1.00) (-0.89)	+0.86 -0.77 (+0.83) (-0.76)	+0.64 -0.53 (+0.54) (-0.47)	+0.10 -0.09 (+0.09) (-0.08)	+0.20 -0.19 (+0.14) (-0.01)
$\mu_{\text{ttH}}^{\text{bb}}$	0.82 <sup>+0.44</sup> <sub>-0.42</sub> (+0.44) (-0.42)	+0.23 -0.23 (+0.23) (-0.22)	+0.24 -0.23 (+0.24) (-0.23)	+0.27 -0.27 (+0.26) (-0.27)	+0.11 -0.03 (+0.11) (-0.04)
$\mu_{\text{ttH}}^{7+8 \text{ TeV}}$	2.59 <sup>+1.01</sup> <sub>-0.88</sub> (+0.87) (-0.79)	+0.54 -0.53 (+0.51) (-0.49)	+0.53 -0.49 (+0.48) (-0.44)	+0.55 -0.49 (+0.50) (-0.44)	+0.37 -0.13 (+0.14) (-0.02)
$\mu_{\text{ttH}}^{13 \text{ TeV}}$	1.14 <sup>+0.31</sup> <sub>-0.27</sub> (+0.29) (-0.26)	+0.17 -0.16 (+0.16) (-0.16)	+0.17 -0.17 (+0.17) (-0.16)	+0.13 -0.12 (+0.13) (-0.12)	+0.14 -0.06 (+0.11) (-0.05)
$\mu_{\text{ttH}}$	1.26 <sup>+0.31</sup> <sub>-0.26</sub> (+0.28) (-0.25)	+0.16 -0.16 (+0.15) (-0.15)	+0.17 -0.15 (+0.16) (-0.15)	+0.14 -0.13 (+0.13) (-0.12)	+0.15 -0.07 (+0.11) (-0.05)

Best fit  $\mu = \sigma/\sigma_{\text{SM}} = 1.26_{-0.26}^{+0.31} = 1.26 \pm 0.16$  (stat)  $_{-0.15}^{+0.17}$  (expt)  $_{-0.13}^{+0.14}$  (bkg th)  $_{-0.07}^{+0.15}$  (sig th)

# Systematic uncertainties

$$\text{Best fit } \mu = \sigma/\sigma_{\text{SM}} = 1.26_{-0.26}^{+0.31} = 1.26 \pm 0.16 \text{ (stat)} \begin{matrix} +0.17 \\ -0.15 \end{matrix} \text{ (expt)} \begin{matrix} +0.14 \\ -0.13 \end{matrix} \text{ (bkg th)} \begin{matrix} +0.15 \\ -0.07 \end{matrix} \text{ (sig th)}$$

## Signal theory

dominated by inclusive ttH cross section and branching ratio

## Background theory

dominated by tt+hf prediction in ttH(bb)

## Experimental

dominated by:

- lepton efficiencies,
- lepton misidentification,
- b-tagging, and
- limited MC statistics

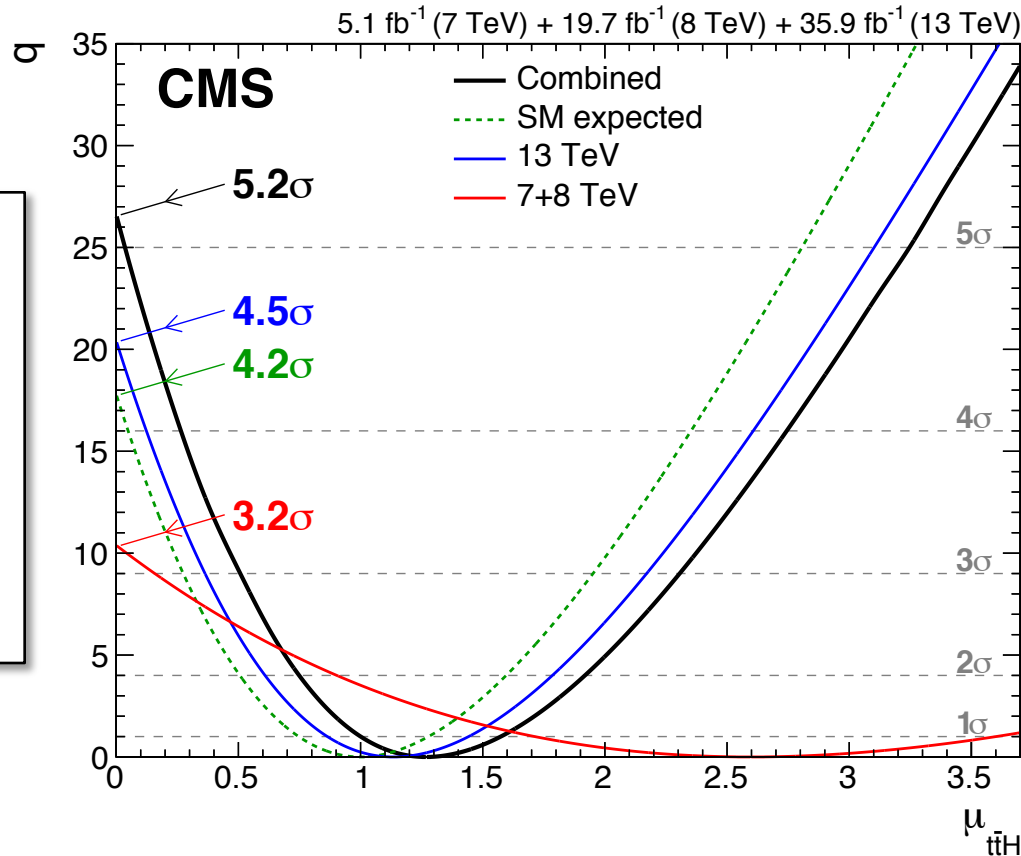
Uncertainty source	$\Delta\mu$	
Signal theory	+0.15	-0.07
Inclusive ttH normalisation (cross section and BR)	+0.15	-0.07
ttH acceptance (scale, pdf, PS and UE)	+0.004	-0.004
Other Higgs boson production modes	+0.002	-0.003
Background theory	+0.14	-0.13
tt + bb/cc prediction	+0.13	-0.11
tt + V(V) prediction	+0.06	-0.06
Other background uncertainties	+0.03	-0.03
Experimental	+0.17	-0.15
Lepton (inc. $\tau_h$ ) trigger, ID and iso. efficiency	+0.08	-0.06
Misidentified lepton prediction	+0.06	-0.06
b-Tagging efficiency	+0.05	-0.04
Jet and $\tau_h$ energy scale and resolution	+0.04	-0.04
Luminosity	+0.04	-0.03
Photon ID, scale and resolution	+0.01	-0.01
Other experimental uncertainties	+0.01	-0.01
Finite number of simulated events	+0.08	-0.07
Statistical	+0.16	-0.16
Total	+0.31	-0.26

Correlations  $\Rightarrow$  sum in quadrature  $>$  total uncertainty

# ttH observation

CMS-HIG-17-035  
arXiv:1804.02610

PRL 120 (2018) 231801



**7+8+13 TeV**

7+8+13 TeV  
(expected)

**13 TeV**

**7+8 TeV**

**First  
observation  
of ttH  
production**

10 April 2018

**Observed (expected) significance 5.2 (4.2) sigma**

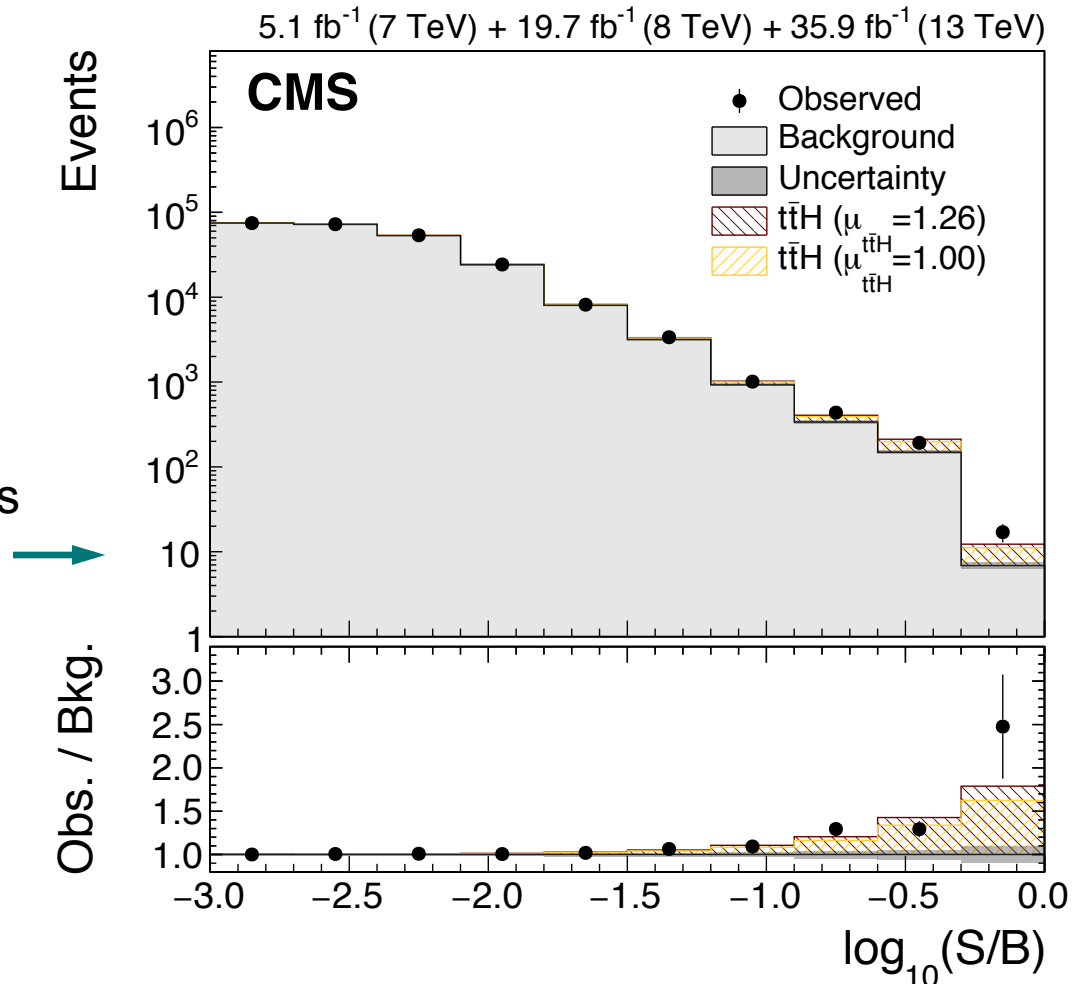
# ttH visualisation

CMS-HIG-17-035  
arXiv:1804.02610

PRL 120 (2018) 231801

- 88 event categories
  - ▶ Many with small excesses
    - Combination is key
  - ▶ Difficult to visualise the excess in any particular category

- Distribution of all events as a function of  $\log_{10}(S/B)$ 
  - ▶ Clear excess visible in the most signal-rich bins



# Conclusion

## Summary

- 5 analyses at 13 TeV measuring ttH
  - ▶ 3 dedicated ttH analyses
    - Including new fully hadronic ttH search
  - ▶ 2 ttH categories of more inclusive analyses
- Combination of 13 TeV analyses with Run 1 ttH analyses
- **Observation of ttH production with  $5.2\sigma$  significance**
  - ▶ First observation of tree-level Higgs–top coupling
  - ▶ Consistent with standard model Higgs within 1 sigma
- Best-fit signal strength  $1.26^{+0.31}_{-0.26}$

## Outlook

- Paves the way for precision ttH measurements
- New data from 2017 currently being analysed
  - ▶ Expect new results soon

# Backup

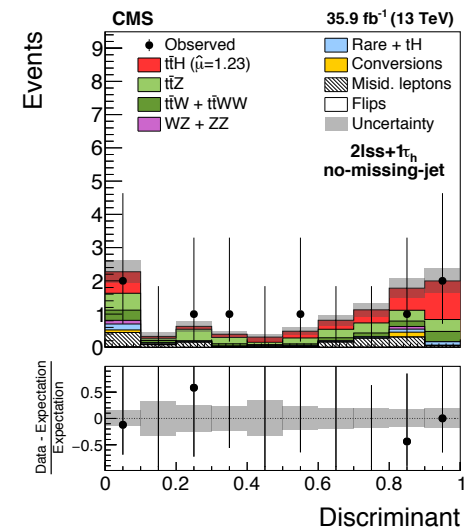
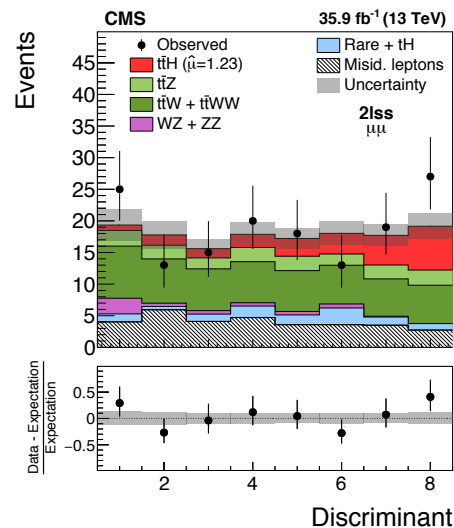
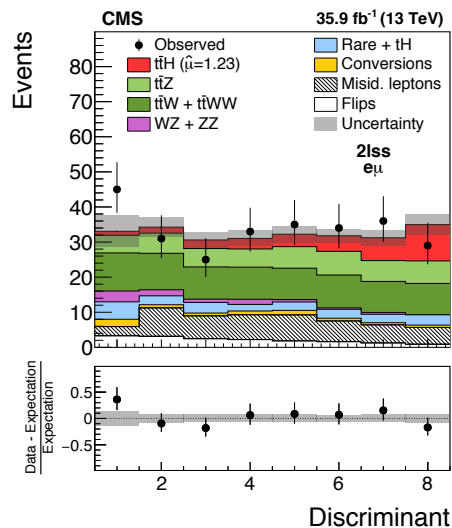




# ttH, multileptons

CMS-HIG-17-018  
arXiv:1803.05485

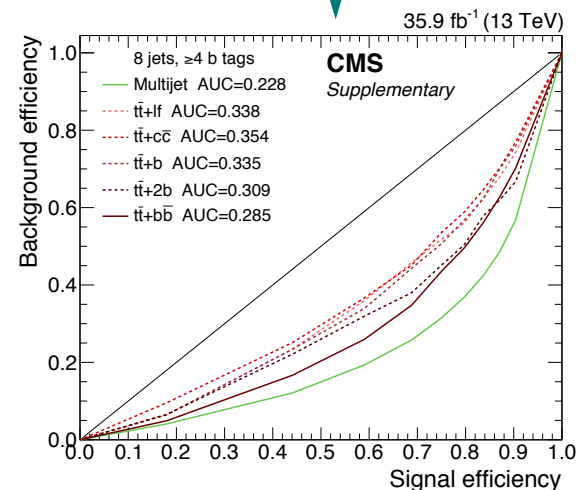
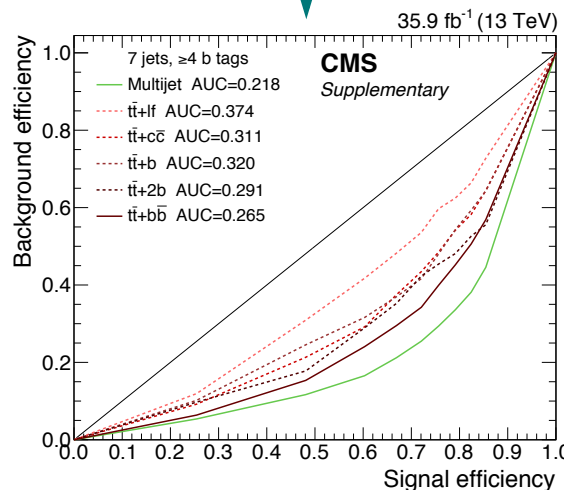
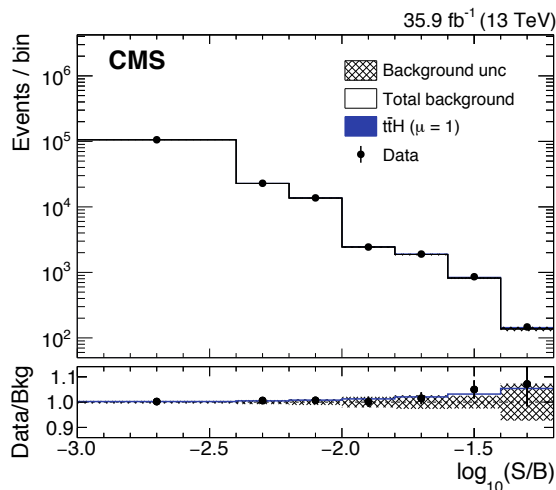
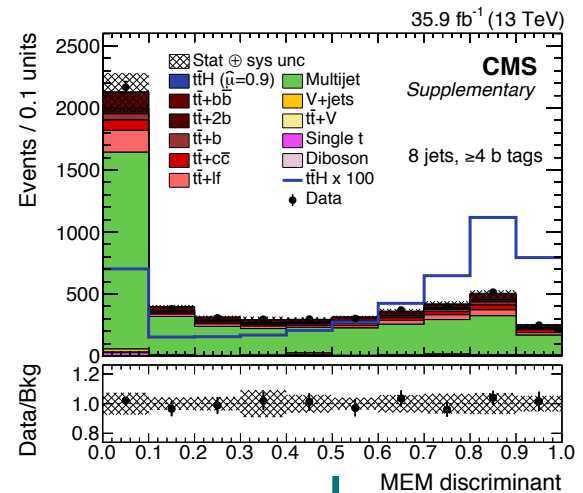
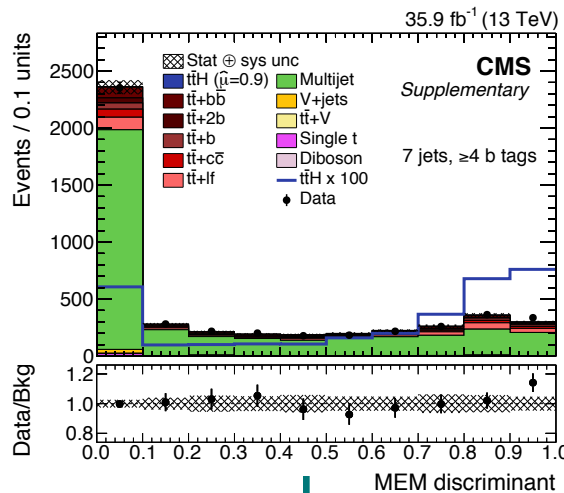
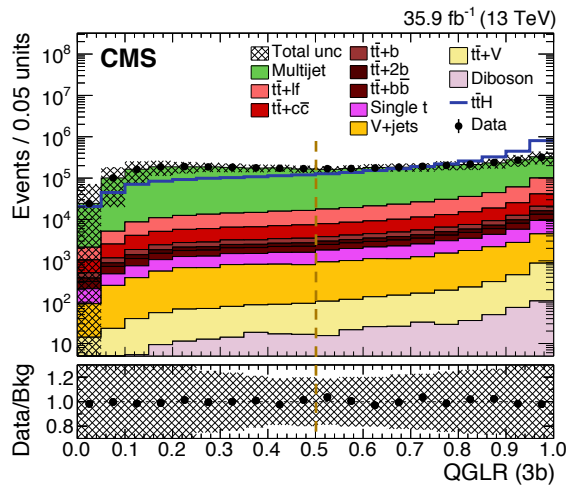
Source	Uncertainty [%]	$\Delta\mu/\mu$ [%]
e, $\mu$ selection efficiency	2–4	11
$\tau_h$ selection efficiency	5	4.5
b tagging efficiency	2–15 [? ]	6
Reducible background estimate	10–40	11
Jet energy calibration	2–15 [? ]	5
$\tau_h$ energy calibration	3	1
Theoretical sources	$\approx 10$	12
Integrated luminosity	2.5	5





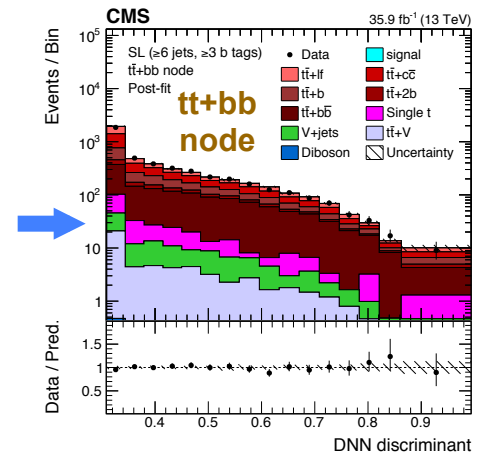
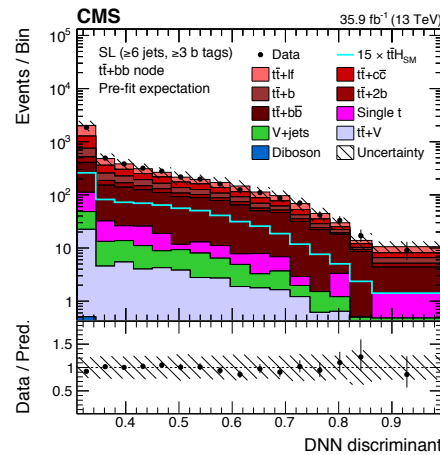
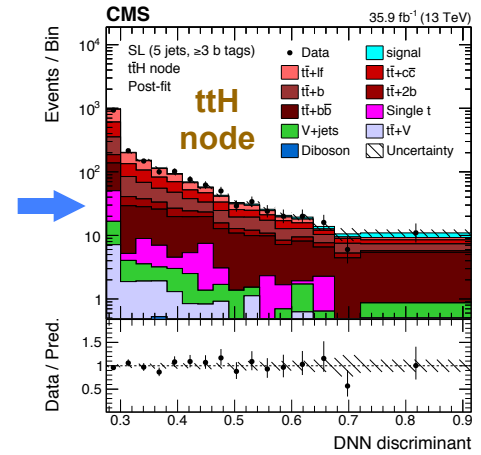
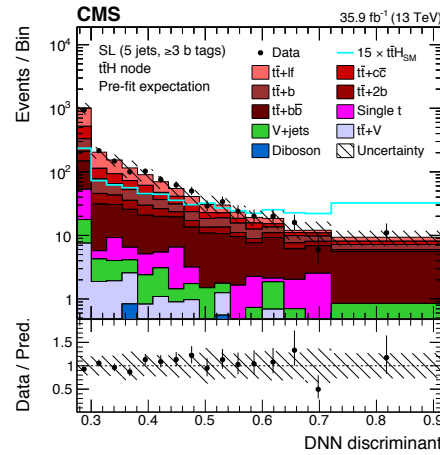
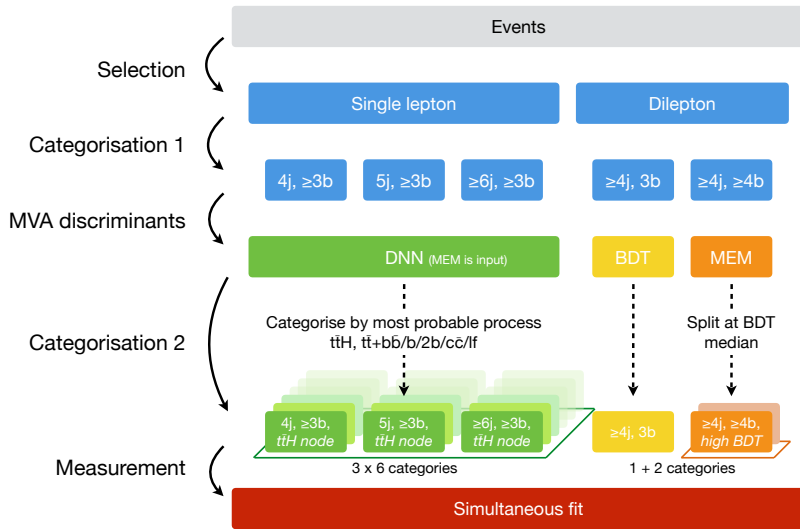
# ttH, H → bb (hadronic)

CMS-HIG-17-022  
arXiv:1803.06986



# ttH, H → bb (leptonic)

CMS-HIG-17-026  
arXiv:1804.03682



Uncertainty source	$\pm\Delta\mu$ (observed)	$\pm\Delta\mu$ (expected)
Total experimental	+0.15/−0.16	+0.19/−0.17
b tagging	+0.11/−0.14	+0.12/−0.11
jet energy scale and resolution	+0.06/−0.07	+0.13/−0.11
Total theory	+0.28/−0.29	+0.32/−0.29
tt+hf cross section and parton shower	+0.24/−0.28	+0.28/−0.28
Size of the simulated samples	+0.14/−0.15	+0.16/−0.16
Total systematic	+0.38/−0.38	+0.45/−0.42
Statistical	+0.24/−0.24	+0.27/−0.27
Total	+0.45/−0.45	+0.53/−0.49

# ttH, H→bb (leptonic)

CMS-HIG-17-026  
arXiv:1804.03682

