Status of ttH and tH searches

Nils Faltermann, 17th Sep. 2018
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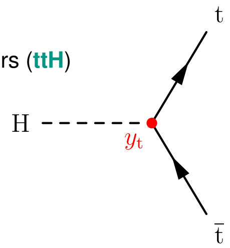
KARLSRUHE INSTITUTE OF TECHNOLOGY (KIT) - INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (ETP)

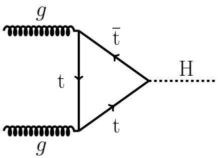
Introduction

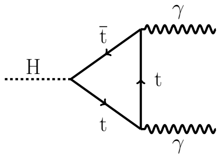
- Goal: probing top-Yukawa interaction y_t
  - Precision test of the standard model
  - Predicted to be ≈ 1, coincidence?
- High coupling strength of the Higgs boson (125 GeV) to top quarks due to high top quark mass (172.5 GeV)
  - But $2m_t > m_H$, so direct $H \rightarrow t\bar{t}$ decay forbidden
- However, the top-Higgs coupling enters the stage on many different levels:
  - Gluon-gluon fusion production (**ggF**)
  - Gamma-gamma branching fraction ($H \rightarrow \gamma\gamma$)
  - Associated production of a Higgs boson with top quark pairs (**ttH**)
  - Associated production with single top quarks (**tH**)
- Experimentally: observe deviations from predicted coupling $\kappa_t = y_t / y_t^{SM}$



Indirect constraints

- Top-Higgs interaction through **fermion loops**:
  - Production via gluon-gluon fusion
  - Decay via gamma-gamma
- But other SM particles can also play a role in the loop
- Furthermore, loop contributions can be modified by BSM physics
- Two different ways to treat these loops:
  - **Unresolved** loops: coupling is treated as effective coupling: κ_g, κ_γ, ...
  - **Resolved** loops: each contribution in the loop is treated with their respective coupling: κ_t, κ_V, ...
- Sensitivity on κ_t strongly depends on the assumptions made
- In either case, BSM physics does not contribute to Higgs branching ratio ($\mathcal{B}_{BSM} = 0$)





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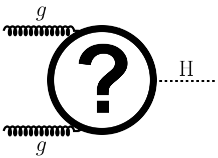
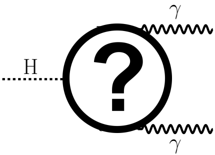
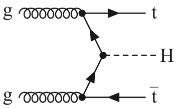
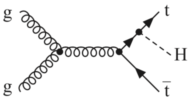


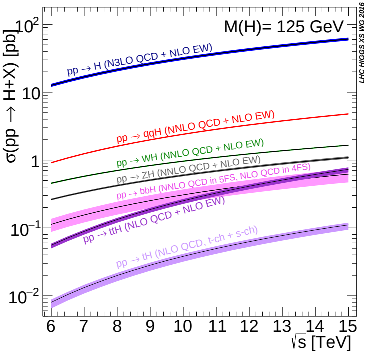


Direct measurements

- Model-independent determination of top-Higgs coupling can only be made in production modes associated with top quarks
  - $t\bar{t}H$: sensitive to κ_t^2
  - tH: sensitive to κ_t and κ_V due to interference of different Feynman diagrams
- Caveat: very low production cross section in comparison with other Higgs boson production modes
  - $\sigma_{t\bar{t}H} = 506.5\,\text{fb}$ (NLO QCD + NLO EW)
  - $\sigma_{tH} = 89.4\,\text{fb}$ (NLO QCD)
- SM $t\bar{t}$ cross section:
  $\sigma_{t\bar{t}} = 831.8\,\text{pb}$ (NNLO QCD)







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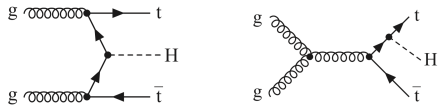
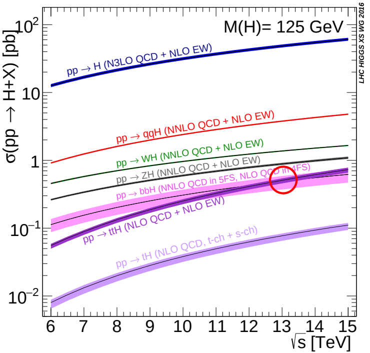
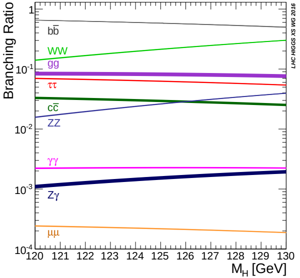




Experimental access to $t\bar{t}H$

- Small signal requires exploiting many different Higgs boson decay channels
  - $H \to b\bar{b}$
  - $H \to \gamma\gamma$
  - $H \to$ multileptons ($\tau\tau$,WW^*,ZZ^*)
- Need also to consider different top quark decay modes
- In general: high branching fractions lead to large background contributions



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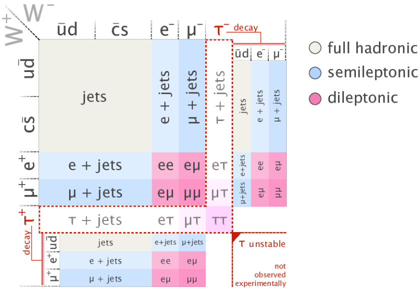

Overview of latest $t\bar{t}H$ results

- Very active research field, recent results and publications on $t\bar{t}H$ production by the ATLAS and CMS collaborations during the last 12 months:
- $H \to b\bar{b}$
  - Phys. Rev. D 97 (2018) 072016 — $36.1\,fb^{-1}$
  - JHEP 06 (2018) 101 — $35.9\,fb^{-1}$
  - arXiv:1804.03682 (Submitted to JHEP) — $35.9\,fb^{-1}$
- $H \to \gamma\gamma$
  - Phys. Lett. B 784 (2018) 173-191 — $79.8\,fb^{-1}$
  - arXiv:1804.02716 (Submitted to JHEP) — $35.9\,fb^{-1}$
- $H \to$ multileptons ($\tau\tau$, WW^*, ZZ^*)
  - Phys. Rev. D 97 (2018) 072003 — $36.1\,fb^{-1}$
  - JHEP 08 (2018) 066 — $35.9\,fb^{-1}$
- Combination of all channels
  - Phys. Lett. B 784 (2018) 173-191 — $36.1\,fb^{-1}/79.8\,fb^{-1}$
  - Phys. Rev. Lett. 120 (2018) 231801 — $35.9\,fb^{-1}$

Search strategy for $t\bar{t}H(b\bar{b})$

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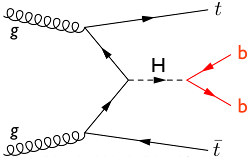
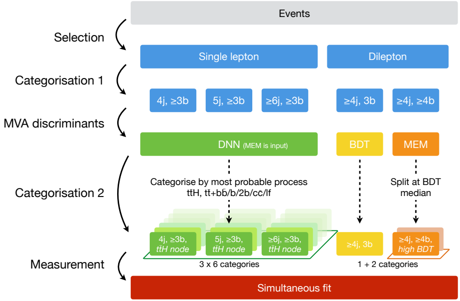
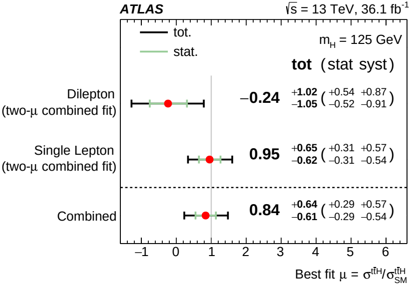
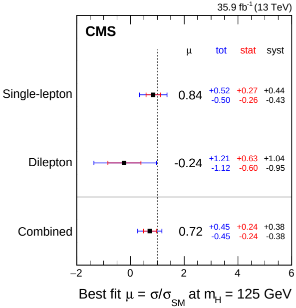
- Highest Higgs boson branching fraction
- Top quarks decay to a bottom quark + W boson
  - Difficult reconstruction of Higgs boson and top quarks due to combinatorics, mass resolution
- Irreducible $t\bar{t}+b\bar{b}$ background
  - Much more likely than signal process, large theory uncertainties
- Top quark pair decay modes: dilepton, lepton+jets and fully-hadronic
- Categorization based on number of jets and b-tagged jets
- Sophisticated multivariate techniques such as BDT, MEM, DNN





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





- Significance: **1.4σ** (1.6σ exp.)
- Dominant uncertainties:
  - Theoretical: $t\bar{t} + \geq 1\ b$
  - Experimental: b tagging

- Significance: **1.6σ** (2.2σ exp.)
- Dominant uncertainties:
  - Theoretical: $t\bar{t} +$ HF
  - Experimental: b tagging

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

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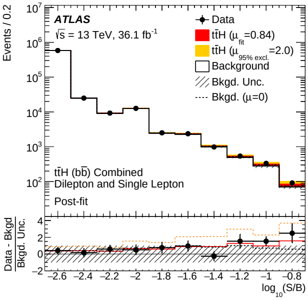

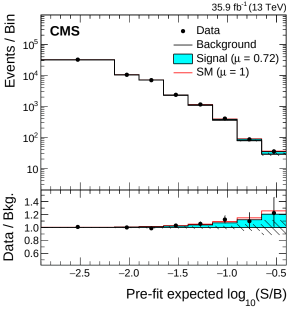

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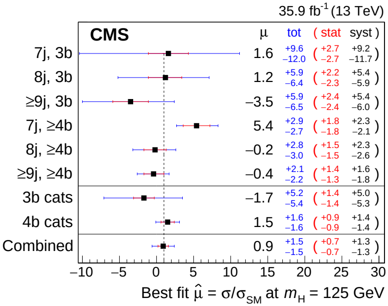
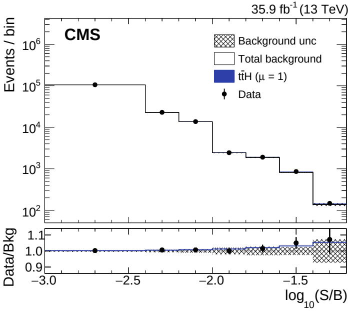
$t\bar{t}H(b\bar{b})$ results (fully-hadronic)

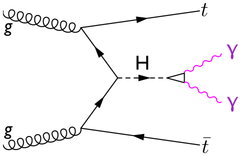


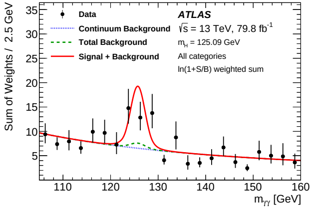


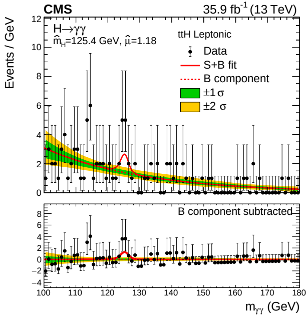
- Upper limit at 95% confidence level:: $\sigma_{t\bar{t}H} < 3.8 \times \sigma_{SM}$ $\left(3.1^{+1.4}_{-0.9} \times \sigma_{SM}\right)$
- Theo. unc.: multijet and $t\bar{t} + $ HF backgrounds
- Exp. unc.: b tagging, jet energy scale

Search strategy for $t\bar{t}H(\gamma\gamma)$

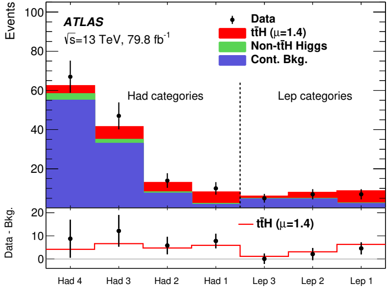
- Excellent mass resolution compared to other decay channels
  - Narrow peak
- Top quark decay channels: leptonic and hadronic
- BDT to reject most non-$t\bar{t}H$ and non-resonant background
- Fit to $m_{\gamma\gamma}$ mass distribution to extract $t\bar{t}H$ signal
- High purity, statistically limited

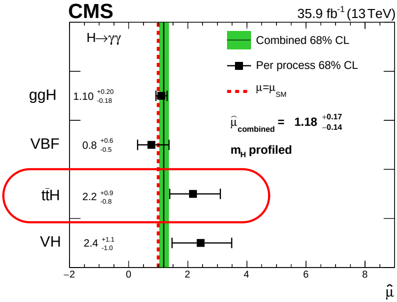






$t\bar{t}H(\gamma\gamma)$ results



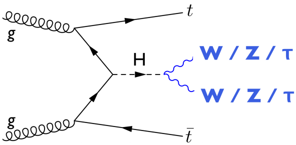


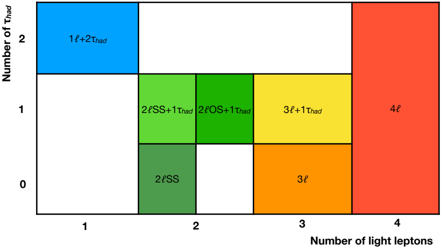
- Significance: **4.1σ** (3.7σ exp.)
- Dominant uncertainties:
  - Theoretical: parton shower modeling
  - Experimental: photon energy resolution

- Part of general $H \rightarrow \gamma\gamma$ analysis
- Dominant uncertainties:
  - Theoretical: QCD scale of background processes
  - Experimental: photon energy resolution

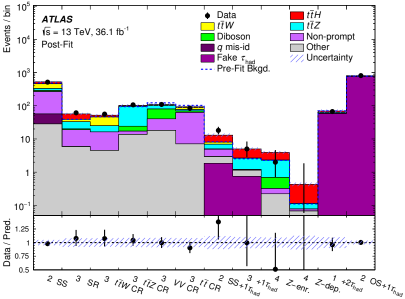
Search strategy for $t\bar{t}H$(multilepton)

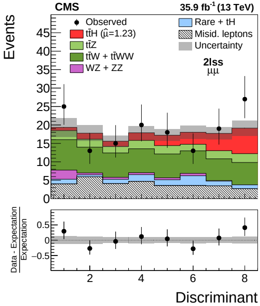
- Analysis to search for leptons from bosonic decays ($H \to WW^*, ZZ^*$) and leptons+hadrons from leptonic decays ($H \to \tau\tau$)
- Additional leptons from top quark decays
- Different event regions with different combinations of up to four leptons and two hadronically decaying tau leptons
  - Charge requirements to effectively reject most $t\bar{t}$ background
- Remaining background:
  - Irreducible $t\bar{t}W$ and $t\bar{t}Z$
  - Fakes, charge flips, misreconstructed τ_{had}
- BDT & MEM





tt̄H(multilepton) results





- Significance: **4.1**σ (2.8σ exp.)
- Dominant uncertainties:
  - Theoretical: signal and tt̄V background modeling
  - Experimental: jet energy scale and resolution

- Significance: **3.2**σ (2.8σ exp.)
- Dominant uncertainties:
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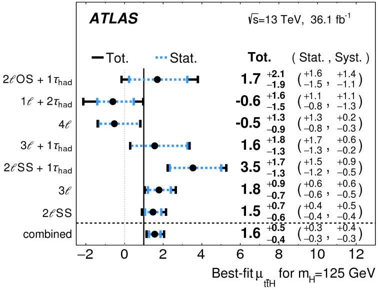
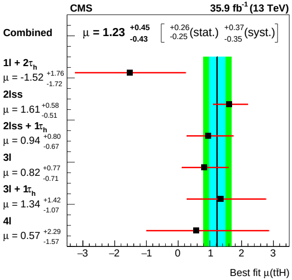
  - Experimental: lepton efficiency and misidentification

$t\bar{t}H$(multilepton) results





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- Dominant uncertainties:
  - Theoretical: signal and $t\bar{t}V$ background modeling
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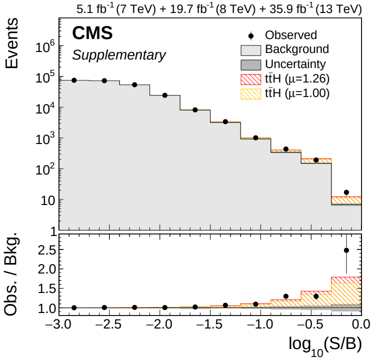
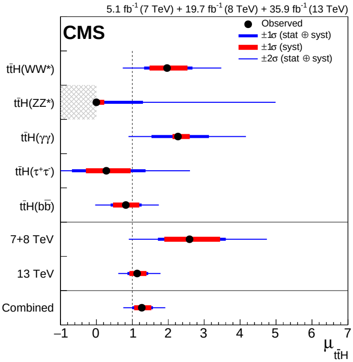
Combination of results

- No single channel excess is significant enough to claim an observation of $t\bar{t}H$ production yet
- Strong evidence for $t\bar{t}H$ production though in single measurements with orthogonal selection
- Statistical combination of results will increase the significance

- Input for the ATLAS combination:
  - Results previously shown for $t\bar{t}H$ production with $H \to b\bar{b}$, $H \to \gamma\gamma$ and $H \to$ multileptons
  - Additional $t\bar{t}H$ category from general $H \to ZZ^* \to 4\ell$ analysis ($79.8\,\text{fb}^{-1}$)
  - Run 1 data at 7 and 8 TeV
- Input for the CMS combination:
  - Results previously shown for $t\bar{t}H$ production with $H \to b\bar{b}$, $H \to \gamma\gamma$ and $H \to$ multileptons
  - Run 1 data at 7 and 8 TeV

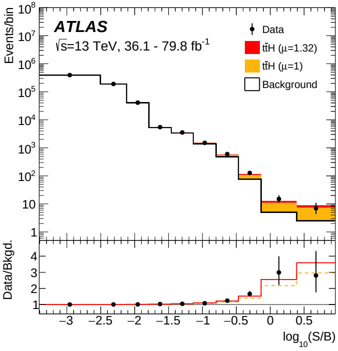
The observation of $t\bar{t}H$ at the CMS experiment

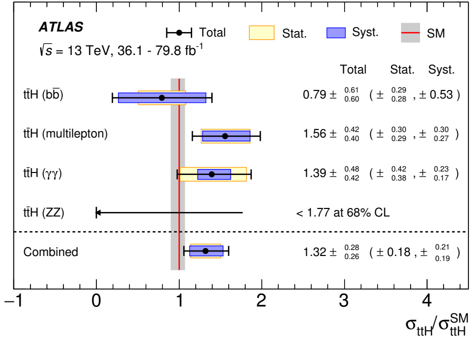




- $\mu = 1.26^{+0.31}_{-0.26} = 1.26 \pm 0.16(\text{stat})\,^{+0.17}_{-0.15}(\text{exp})\,^{+0.14}_{-0.13}(\text{th,B})\,^{+0.15}_{-0.07}(\text{th,S})$
- Significance with 7, 8 and 13 TeV data: **5.2σ** (4.2σ exp.)

The observation of $t\bar{t}H$ at the ATLAS experiment

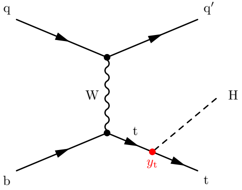


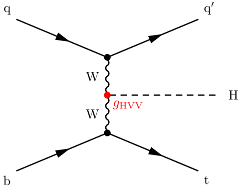


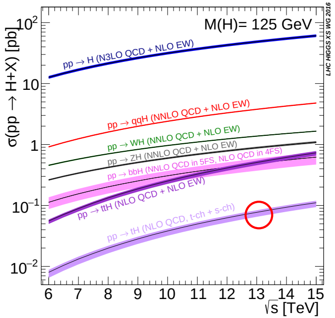
- $\mu = 1.32^{+0.28}_{-0.26} = 1.32 \pm 0.18(\text{stat})\,^{+0.21}_{-0.19}(\text{syst})$
- Significance with 13 TeV data only: **5.8σ** (4.9σ exp.)
- Significance with 7, 8 and 13 TeV data: **6.3σ** (5.1σ exp.)

Beyond $t\bar{t}H$ ... search for tH production

- Production cross section for tH even lower than for $t\bar{t}H$
- But coupling not only to top quarks, but also to W bosons
- Strongly sensitive to variations of the top-Yukava coupling y_t, the coupling to vector bosons g_{HVV} and a relative minus sign between both couplings
- Interference of diagrams, destructive in the SM







- Single top quark production modes:
  - *t* channel (**tHq**)
  - associated tW (**tHW**)
  - *s* channel (negligible)

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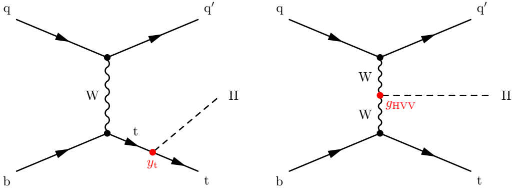

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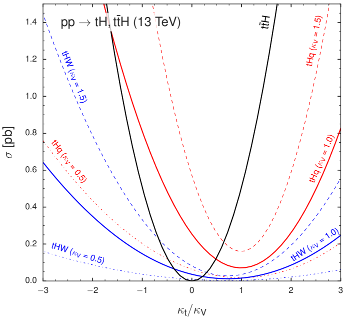

Search for tH(multilepton) **CMS-PAS-HIG-17-005**

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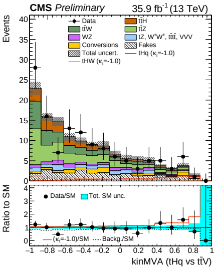
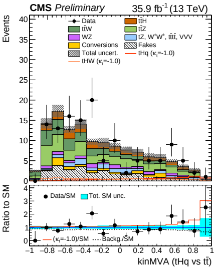
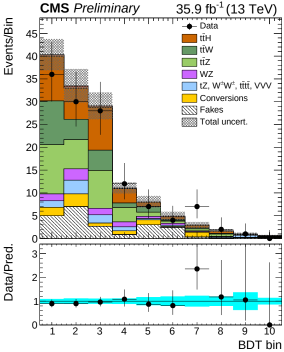
- $t\bar{t}H$ multilepton analysis as baseline ($35.9\,\mathrm{fb}^{-1}$)
- Event categories with three leptons, $\mu^{\pm}\mu^{\pm}$, or $\mu^{\pm}e^{\pm}$
- Two BDTs trained for most sensitive BSM scenario ($\kappa_t = -1$)
  - Background from $t\bar{t}W$ and $t\bar{t}Z$
  - Background from non-prompt leptons ($t\bar{t}$)
- 2D BDT output mapped to 1D distribution



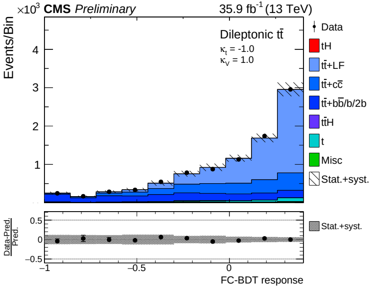


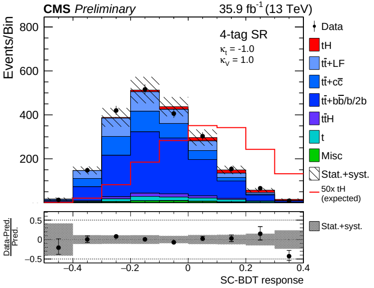


Search for tH($b\bar{b}$)

CMS-PAS-HIG-17-016

- Event categories with one lepton, three or four b-tagged and at least one untagged jet
- Final state reconstruction with multivariate approach:
  - Different jet assignment BDTs for different event hypotheses (tHq, tHW, $t\bar{t}$)
  - Extract process-sensitive variables (e.g. m_H)
  - Final event classification BDT
- Additional dilepton region to constrain different flavor of $t\bar{t}$+X background

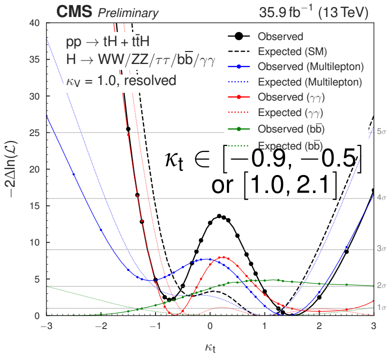


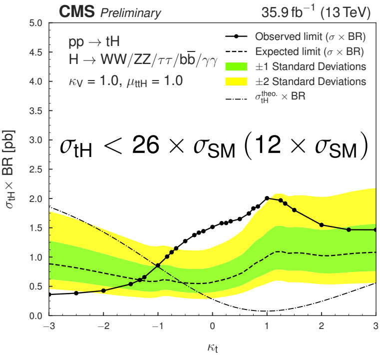


Combination of tH results

CMS-PAS-HIG-18-009

- Combination of results from the two dedicated tH production searches
  - Additionally sensitivity from $t\bar{t}H$ categories of $H \rightarrow \gamma\gamma$ analysis
  - Efficiency and acceptance corrected for different κ_t scenario
- Likelihood scan to constrain κ_t for combined $t\bar{t}H$+tH production
- Exclusion limits for tH production with fixed SM-$t\bar{t}H$ production

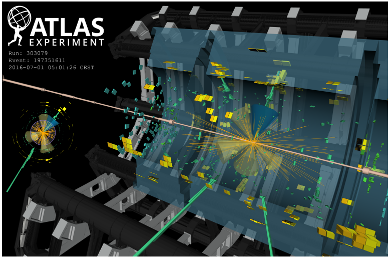


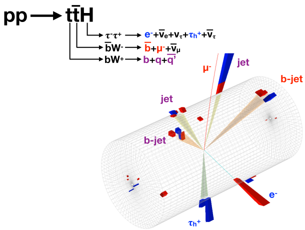


Summary

Karlsruhe Institute of Technology

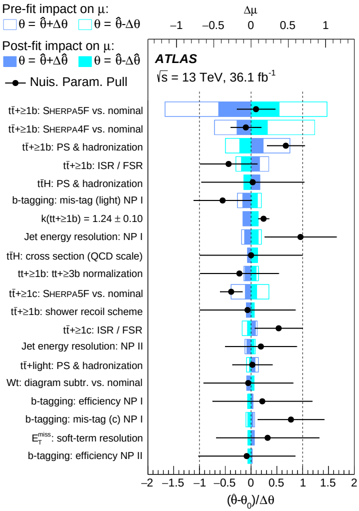
- Recent results on searches for $t\bar{t}H$ and tH production at the LHC
- Heavy usage of multivariate analysis techniques
- Observation of $t\bar{t}H$ observation from two independent experiments
- One of the major milestones for Run II at the LHC
  - Large fraction of Run II data still has to be analyzed
  - Some channels already systematically limited
- tH production helps to further constrain Higgs boson couplings





Backup

ATLAS $t\bar{t}H(b\bar{b})$



ATLAS $t\bar{t}H(b\bar{b})$

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

CMS $t\bar{t}H(b\bar{b})$

Process	SL channel	DL channel
$t\bar{t}$+lf	463 658 ± 174	241 032 ± 99
$t\bar{t}$+$c\bar{c}$	76 012 ± 70	24 550 ± 32
$t\bar{t}$+b	22 416 ± 38	5 979 ± 16
$t\bar{t}$+2b	9 052 ± 24	1 785 ± 9
$t\bar{t}$+$b\bar{b}$	10 897 ± 27	1 840 ± 9
Single t	25 215 ± 166	12 206 ± 125
V+jets	12 309 ± 58	5 684 ± 209
$t\bar{t}$+V	2 457 ± 12	2 570 ± 23
Diboson	449 ± 14	430 ± 15
Total bkg.	622 466 ± 263	296 077 ± 266
$t\bar{t}$H	1 232 ± 2	314.0 ± 0.9
Data	610 556	283 942

CMS $t\bar{t}H(b\bar{b})$

Source	Type	Remarks
Integrated luminosity	rate	Signal and all backgrounds
Lepton identification/isolation	shape	Signal and all backgrounds
Trigger efficiency	shape	Signal and all backgrounds
Pileup	shape	Signal and all backgrounds
Jet energy scale	shape	Signal and all backgrounds
Jet energy resolution	shape	Signal and all backgrounds
b tag hf fraction	shape	Signal and all backgrounds
b tag hf stats (linear)	shape	Signal and all backgrounds
b tag hf stats (quadratic)	shape	Signal and all backgrounds
b tag lf fraction	shape	Signal and all backgrounds
b tag lf stats (linear)	shape	Signal and all backgrounds
b tag lf stats (quadratic)	shape	Signal and all backgrounds
b tag charm (linear)	shape	Signal and all backgrounds
b tag charm (quadratic)	shape	Signal and all backgrounds
Renorm./fact. scales ($t\bar{t}H$)	rate	Scale uncertainty of NLO $t\bar{t}H$ prediction
Renorm./fact. scales ($t\bar{t}$)	rate	Scale uncertainty of NLO $t\bar{t}$ prediction
Renorm./fact. scales ($t\bar{t}$+hf)	rate	Additional 50% rate uncertainty of $t\bar{t}$+hf predictions
Renorm./fact. scales (t)	rate	Scale uncertainty of NLO single t prediction
Renorm./fact. scales (V)	rate	Scale uncertainty of NNLO W and Z prediction
Renorm./fact. scales (VV)	rate	Scale uncertainty of NLO diboson prediction
PDF (gg)	rate	PDF uncertainty for gg initiated processes except $t\bar{t}H$
PDF (gg $t\bar{t}H$)	rate	PDF uncertainty for $t\bar{t}H$
PDF ($q\bar{q}$)	rate	PDF uncertainty of $q\bar{q}$ initiated processes ($t\bar{t}$+W,W,Z)
PDF (qg)	rate	PDF uncertainty of qg initiated processes (single t)
μ_R scale ($t\bar{t}$)	shape	Renormalisation scale uncertainty of the $t\bar{t}$ ME generator, independent for additional jet flavours
μ_F scale ($t\bar{t}$)	shape	Factorisation scale uncertainty of the $t\bar{t}$ ME generator, independent for additional jet flavours
PS scale: ISR ($t\bar{t}$)	rate	Initial state radiation uncertainty of the PS (for $t\bar{t}$ events), jet multiplicity dependent rate uncertainty, independent for additional jet flavours
PS scale: FSR ($t\bar{t}$)	rate	Final state radiation uncertainty (for $t\bar{t}$ events), jet multiplicity dependent rate uncertainty, independent for additional jet flavours
ME-PS matching ($t\bar{t}$)	rate	NLO ME to PS matching, *hdamp* [?] (for $t\bar{t}$ events), jet multiplicity dependent rate uncertainty, independent for additional jet flavours
Underlying event ($t\bar{t}$)	rate	Underlying event (for $t\bar{t}$ events), jet multiplicity dependent rate uncertainty, independent for additional jet flavours
NNPDF3.0NLO ($t\bar{t}H$, $t\bar{t}$)	shape	Based on the NNPDF replicas, same for $t\bar{t}H$ and additional jet flavours
Bin-by-bin event count	shape	Statistical uncertainty of the signal and background prediction due to the limited sample size

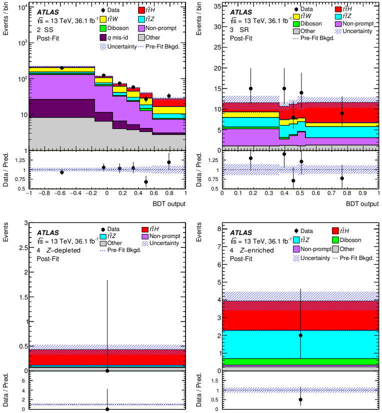
CMS $t\bar{t}H(b\bar{b})$

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
$t\bar{t}$+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

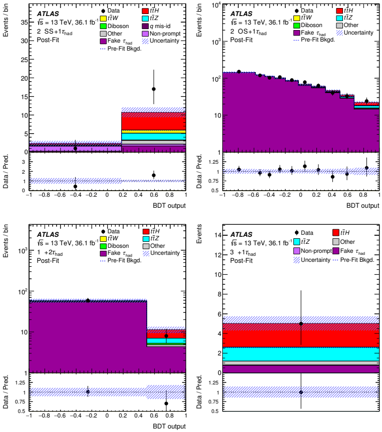
CMS $t\bar{t}H(b\bar{b})$

Channel	Method	Best-fit μ $\pm$tot ($\pm$stat $\pm$ syst)
Single-lepton	BDT+MEM	$1.0^{+0.69}_{-0.66}\ \left(^{+0.31}_{-0.30}\ ^{+0.62}_{-0.59}\right)$
Single-lepton	DNN	$1.0^{+0.58}_{-0.55}\ \left(^{+0.30}_{-0.29}\ ^{+0.50}_{-0.47}\right)$
Dilepton	BDT+MEM	$1.0^{+1.22}_{-1.12}\ \left(^{+0.65}_{-0.62}\ ^{+1.04}_{-0.93}\right)$
Dilepton	DNN	$1.0^{+1.38}_{-1.36}\ \left(^{+0.71}_{-0.69}\ ^{+1.18}_{-1.18}\right)$
Combined	BDT+MEM	$1.0^{+0.60}_{-0.57}\ \left(^{+0.28}_{-0.27}\ ^{+0.53}_{-0.51}\right)$
Combined	DNN	$1.0^{+0.55}_{-0.51}\ \left(^{+0.27}_{-0.27}\ ^{+0.47}_{-0.44}\right)$

ATLAS $t\bar{t}H$(multilepton)



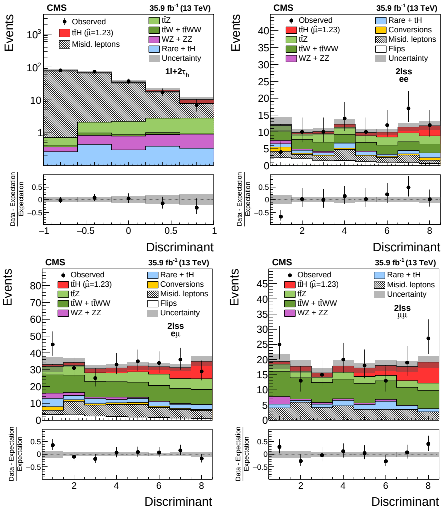
ATLAS $t\bar{t}H$(multilepton)



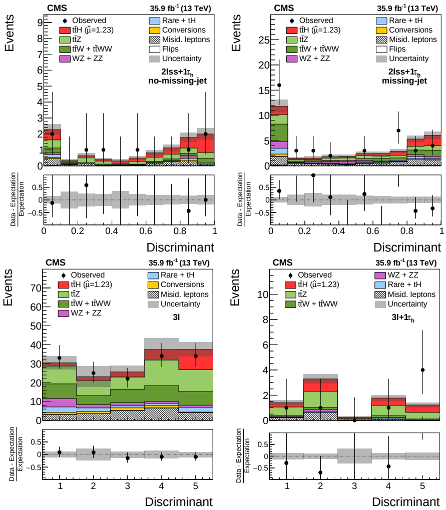
ATLAS $t\bar{t}H$(multilepton)

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

CMS tt̄H(multilepton)



CMS $t\bar{t}$H(multilepton)



CMS $t\bar{t}H$(multilepton)

Process	$1\ell + 2\tau_h$	$2\ell ss$	$2\ell ss + 1\tau_h$
$t\bar{t}H$	5.8 ± 1.9	53.8 ± 17.0	$9.4 \pm ^{2.8}$
$t\bar{t}Z/\gamma^*$	6.3 ± 1.1	80.9 ± 10.4	9.2 ± 1.2
$t\bar{t}W + t\bar{t}WW$	0.5 ± 0.1	150.0 ± 16.9	9.1 ± 1.0
$WZ + ZZ$	2.1 ± 1.6	16.5 ± 13.1	3.9 ± 3.0
tH	0.4 ± 0.1	2.7 ± 0.2	0.5 ± 0.04
Conversions	< 0.02	12.1 ± 5.8	1.4 ± 0.5
Sign flip	—	27.5 ± 8.0	0.5 ± 0.1
Misidentified leptons	195.7 ± 13.6	94.2 ± 21.2	8.6 ± 2.1
Rare backgrounds	1.4 ± 0.7	39.0 ± 21.2	$3.1 \pm ^{1.5}$
Total expected background	206.3 ± 14.0	423.0 ± 38.0	$36.1 \pm ^{4.2}$
Observed	212	507	49

Process	3ℓ	$3\ell + 1\tau_h$	4ℓ
$t\bar{t}H$	18.5 ± 6.0	2.1 ± 0.7	$0.9 \pm ^{0.3}$
$t\bar{t}Z/\gamma^*$	49.0 ± 6.9	3.4 ± 0.5	2.1 ± 0.4
$t\bar{t}W + t\bar{t}WW$	35.2 ± 4.2	0.4 ± 0.04	$< 2 \times 10^{-3}$
$WZ + ZZ$	9.9 ± 2.4	0.3 ± 0.05	0.1 ± 0.1
tH	1.2 ± 0.2	0.1 ± 0.01	$< 4 \times 10^{-4}$
Conversions	5.3 ± 2.9	< 0.02	< 0.02
Misidentified leptons	22.7 ± 6.7	0.9 ± 0.2	< 0.04
Rare backgrounds	8.2 ± 13.8	0.2 ± 0.1	$0.1 \pm ^{0.2}$
Total expected background	131.4 ± 18.2	5.3 ± 0.5	$2.4 \pm ^{0.4}$
Observed	148	7	3

CMS $t\bar{t}H$(multilepton)

Category	Observed limit on μ	Expected limit ($\mu = 0$)	Expected limit ($\mu = 1$)
$1\ell + 2\tau_h$	2.7	$4.1^{+1.7}_{-1.4}$	$4.8^{+2.0}_{-1.9}$
$2\ell ss$	2.8	$1.0^{+0.4}_{-0.2}$	$2.0^{+0.7}_{-0.3}$
$2\ell ss + 1\tau_h$	2.5	$1.4^{+0.7}_{-0.3}$	$2.5^{+0.9}_{-0.5}$
3ℓ	2.7	$1.6^{+0.8}_{-0.4}$	$2.9^{+1.1}_{-0.4}$
$3\ell + 1\tau_h$	4.4	$2.8^{+1.3}_{-0.6}$	$4.1^{+1.5}_{-0.7}$
4ℓ	6.5	$4.9^{+2.8}_{-1.1}$	$6.7^{+2.5}_{-0.8}$
Combined	2.1	$0.8^{+0.3}_{-0.2}$	$1.7^{+0.5}_{-0.5}$

ATLAS $t\bar{t}H$ combination

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(11)	0.49(33)	1.76(55)	6.4(13)	10
Had 2	3.41(74)	0.69(56)	7.5(11)	11.6(15)	14
Had 3	4.70(88)	2.0(17)	32.9(22)	39.6(32)	47
Had 4	3.00(55)	3.2(31)	55.0(28)	61.3(47)	67
Lep 1	4.5(10)	0.25(9)	2.19(59)	6.9(12)	7
Lep 2	2.23(39)	0.27(10)	4.59(91)	7.1(10)	7
Lep 3	0.82(18)	0.30(13)	4.58(91)	5.70(88)	5
			$H \to ZZ^* \to 4\ell$		
Had 1	0.169(31)	0.021(7)	0.008(8)	0.198(33)	0
Had 2	0.216(32)	0.20(9)	0.22(12)	0.63(16)	0
Lep	0.212(31)	0.0256(23)	0.015(13)	0.253(34)	0

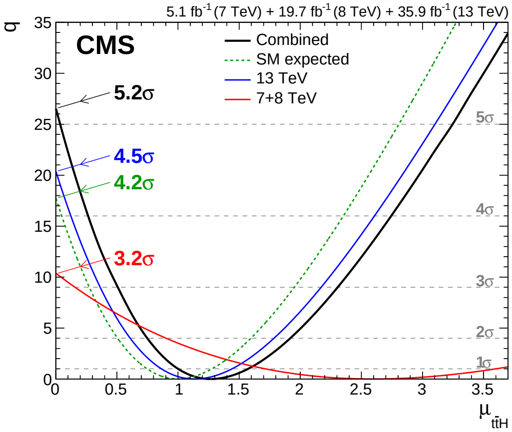
ATLAS $t\bar{t}H$ combination

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

ATLAS $t\bar{t}H$ combination

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.)	$4.1\ \sigma$	$3.7\ \sigma$
$H \to$ multilepton	36.1	790 ± 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 ± 90 (stat.) $^{+110}_{-100}$ (syst.)	$5.8\ \sigma$	$4.9\ \sigma$
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1−79.8	–	$6.3\ \sigma$	$5.1\ \sigma$

CMS $t\bar{t}H$ combination



CMS $t\bar{t}H$ combination

		Uncertainty			
Parameter	Best fit	Stat	Expt	Thbgd	Thsig
$\mu_{t\bar{t}H}^{WW^*}$	$1.97^{+0.71}_{-0.64}$	$^{+0.42}_{-0.41}$	$^{+0.46}_{-0.42}$	$^{+0.21}_{-0.21}$	$^{+0.25}_{-0.12}$
	$\left(^{+0.57}_{-0.54}\right)$	$\left(^{+0.39}_{-0.38}\right)$	$\left(^{+0.36}_{-0.34}\right)$	$\left(^{+0.17}_{-0.17}\right)$	$\left(^{+0.12}_{-0.03}\right)$
$\mu_{t\bar{t}H}^{ZZ^*}$	$0.00^{+1.30}_{-0.00}$	$^{+1.28}_{-0.00}$	$^{+0.20}_{-0.00}$	$^{+0.04}_{-0.00}$	$^{+0.09}_{-0.00}$
	$\left(^{+2.89}_{-0.99}\right)$	$\left(^{+2.82}_{-0.99}\right)$	$\left(^{+0.51}_{-0.00}\right)$	$\left(^{+0.15}_{-0.00}\right)$	$\left(^{+0.27}_{-0.00}\right)$
$\mu_{t\bar{t}H}^{\gamma\gamma}$	$2.27^{+0.86}_{-0.74}$	$^{+0.80}_{-0.72}$	$^{+0.15}_{-0.09}$	$^{+0.02}_{-0.01}$	$^{+0.29}_{-0.13}$
	$\left(^{+0.73}_{-0.64}\right)$	$\left(^{+0.71}_{-0.64}\right)$	$\left(^{+0.09}_{-0.04}\right)$	$\left(^{+0.01}_{-0.00}\right)$	$\left(^{+0.13}_{-0.05}\right)$
$\mu_{t\bar{t}H}^{\tau^+\tau^-}$	$0.28^{+1.09}_{-0.96}$	$^{+0.86}_{-0.77}$	$^{+0.64}_{-0.53}$	$^{+0.10}_{-0.09}$	$^{+0.20}_{-0.19}$
	$\left(^{+1.00}_{-0.89}\right)$	$\left(^{+0.83}_{-0.76}\right)$	$\left(^{+0.54}_{-0.47}\right)$	$\left(^{+0.09}_{-0.08}\right)$	$\left(^{+0.14}_{-0.01}\right)$
$\mu_{t\bar{t}H}^{b\bar{b}}$	$0.82^{+0.44}_{-0.42}$	$^{+0.23}_{-0.23}$	$^{+0.24}_{-0.23}$	$^{+0.27}_{-0.27}$	$^{+0.11}_{-0.03}$
	$\left(^{+0.44}_{-0.42}\right)$	$\left(^{+0.23}_{-0.22}\right)$	$\left(^{+0.24}_{-0.23}\right)$	$\left(^{+0.26}_{-0.27}\right)$	$\left(^{+0.11}_{-0.04}\right)$
$\mu_{t\bar{t}H}^{7+8\ \mathrm{TeV}}$	$2.59^{+1.01}_{-0.88}$	$^{+0.54}_{-0.53}$	$^{+0.53}_{-0.49}$	$^{+0.55}_{-0.49}$	$^{+0.37}_{-0.13}$
	$\left(^{+0.87}_{-0.79}\right)$	$\left(^{+0.51}_{-0.49}\right)$	$\left(^{+0.48}_{-0.44}\right)$	$\left(^{+0.50}_{-0.44}\right)$	$\left(^{+0.14}_{-0.02}\right)$
$\mu_{t\bar{t}H}^{13\ \mathrm{TeV}}$	$1.14^{+0.31}_{-0.27}$	$^{+0.17}_{-0.16}$	$^{+0.17}_{-0.17}$	$^{+0.13}_{-0.12}$	$^{+0.14}_{-0.06}$
	$\left(^{+0.29}_{-0.26}\right)$	$\left(^{+0.16}_{-0.16}\right)$	$\left(^{+0.17}_{-0.16}\right)$	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.11}_{-0.05}\right)$
$\mu_{t\bar{t}H}$	$1.26^{+0.31}_{-0.26}$	$^{+0.16}_{-0.16}$	$^{+0.17}_{-0.15}$	$^{+0.14}_{-0.13}$	$^{+0.15}_{-0.07}$
	$\left(^{+0.28}_{-0.25}\right)$	$\left(^{+0.15}_{-0.15}\right)$	$\left(^{+0.16}_{-0.15}\right)$	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.11}_{-0.05}\right)$

CMS $t\bar{t}H$ combination

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. τ_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 τ_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