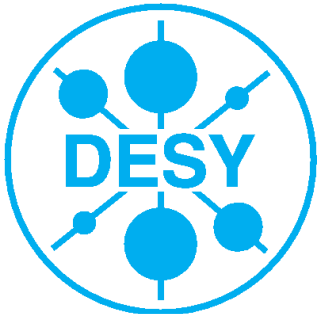
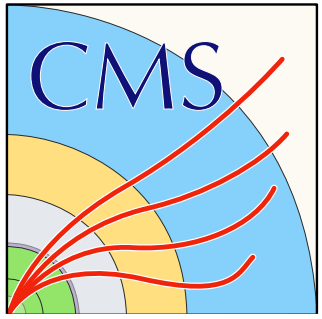




Measurements of $t\bar{t}H$ and tH production (with focus on multilepton and $H \to b\bar{b}$ channels)

Marino Missiroli (DESY),

on behalf of the ATLAS and CMS Collaborations

SM@LHC 2019

Zurich, 23-26 April 2019

Outline

- the top-Higgs coupling
- the observation of $t\bar{t}H$ production at ATLAS and CMS
- a closer look at:
  - $t\bar{t}H$ with $H \to b\bar{b}$
  - $t\bar{t}H$ in multilepton final states
- tH production:
  - dedicated searches with $H \to b\bar{b}$ and multilepton final states
  - combination of tH searches

The Top-Higgs coupling

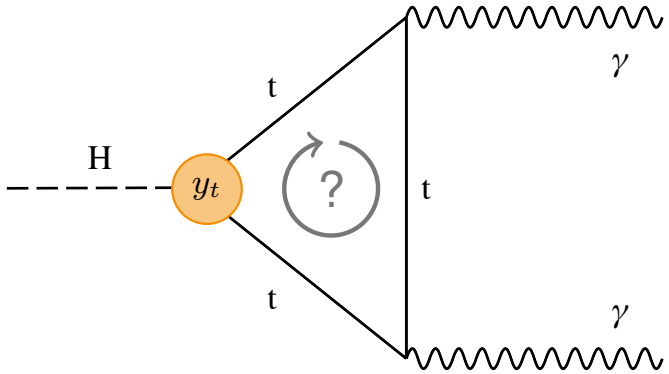
- Higgs coupling to fermions:
  - key test of properties of $H(125)$
  - SM: coupling proportial to m_f

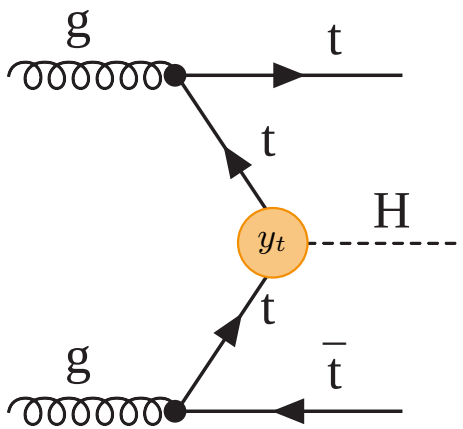
- Top quark: heaviest elementary particle, strongest coupling to SM Higgs ($y_t \simeq 1$)
  - ggH production and $H \to \gamma\gamma$: indirect evidence of top-Higgs coupling
  - direct measurement of top-Higgs coupling at the LHC: $t\bar{t}H$ and tH cross sections

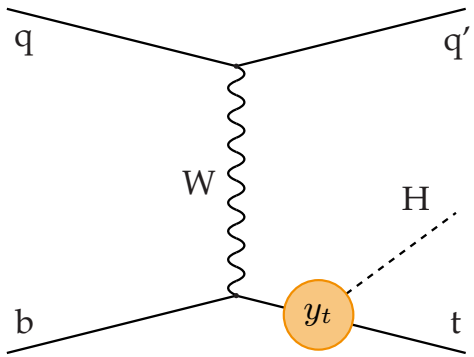
$\sigma_{t\bar{t}H} \simeq 0.5$ pb : best sensitivity to $|y_t|$

$\sigma_{tH} \simeq 0.1$ pb : sensitive to sign of y_t

[13TeV SM cross sections]







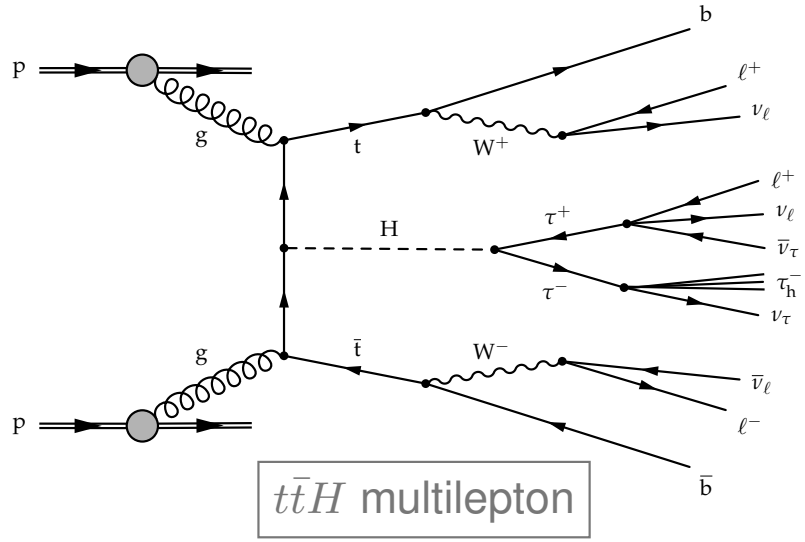
$t\bar{t}H$ observation

ATLAS : HIGG-2018-13, Phys. Lett. B 784 (2018) 173

CMS : HIG-17-035, Phys. Rev. Lett. 120 (2018) 231801

$t\bar{t}H$ analysis channels

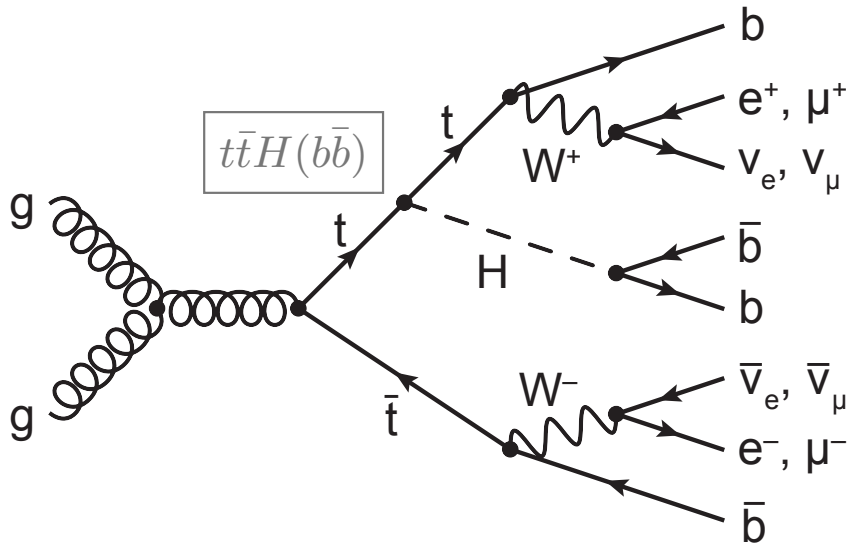
- $t\bar{t}H$ multilepton:
  - targets $H \to WW^*, ZZ^*, \tau^+\tau^-$
  - 2 same-sign or $\geqslant 3$ charged leptons, including hadronic τ decays



$t\bar{t}H$ multilepton

- $t\bar{t}H$ with $H \to b\bar{b}$ decays:
  - 0, 1 or 2 leptons + jets (with up to 4 b-jets)

- $t\bar{t}H$ with $H \to \gamma\gamma$ and $H \to 4\ell$ decays:
  - high purity, but lowest signal yields
  - excess in inv-mass of Higgs candidate

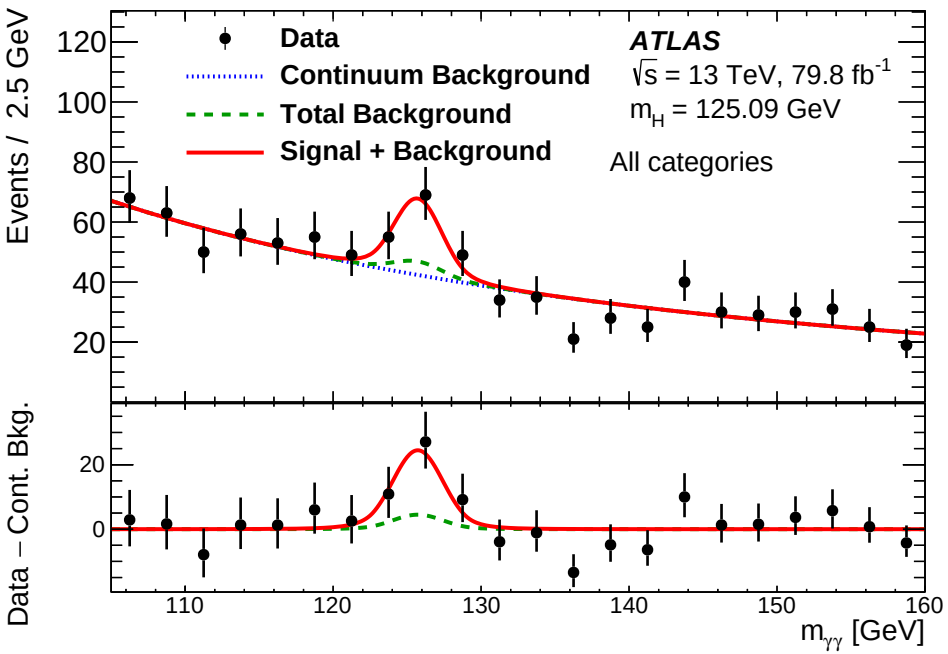


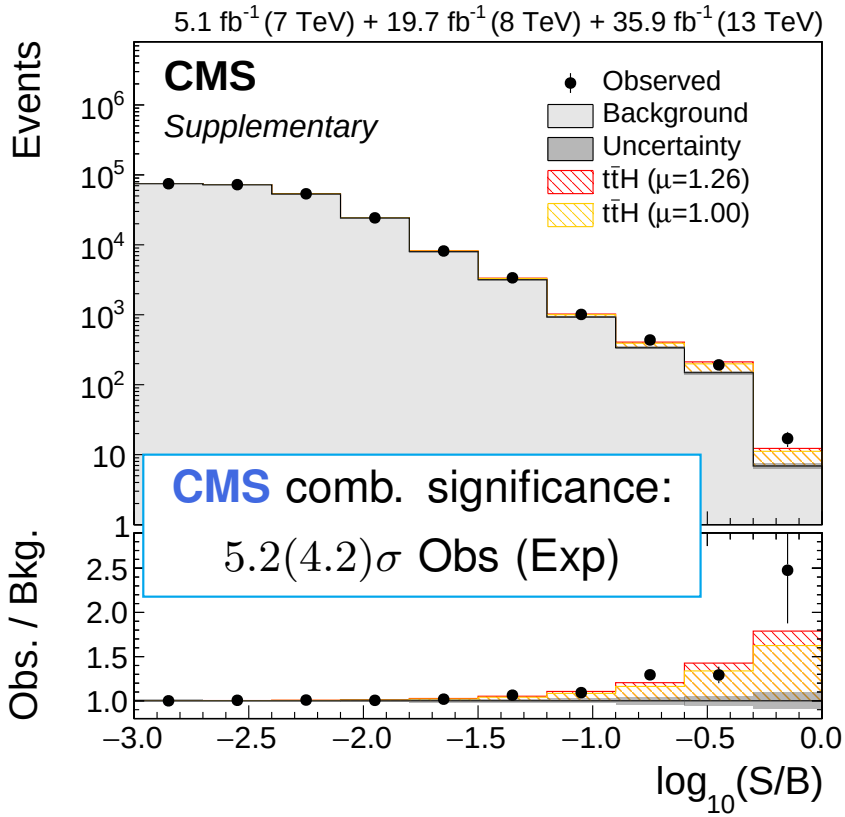
Observation of $t\bar{t}H$ production

Combination of $t\bar{t}H$ searches in ATLAS and CMS

- In 2018, ATLAS and CMS combined all available ttH analyses and reached the observation mark for this production mode

ATLAS comb. significance: $6.3(5.1)\sigma$ Obs (Exp)



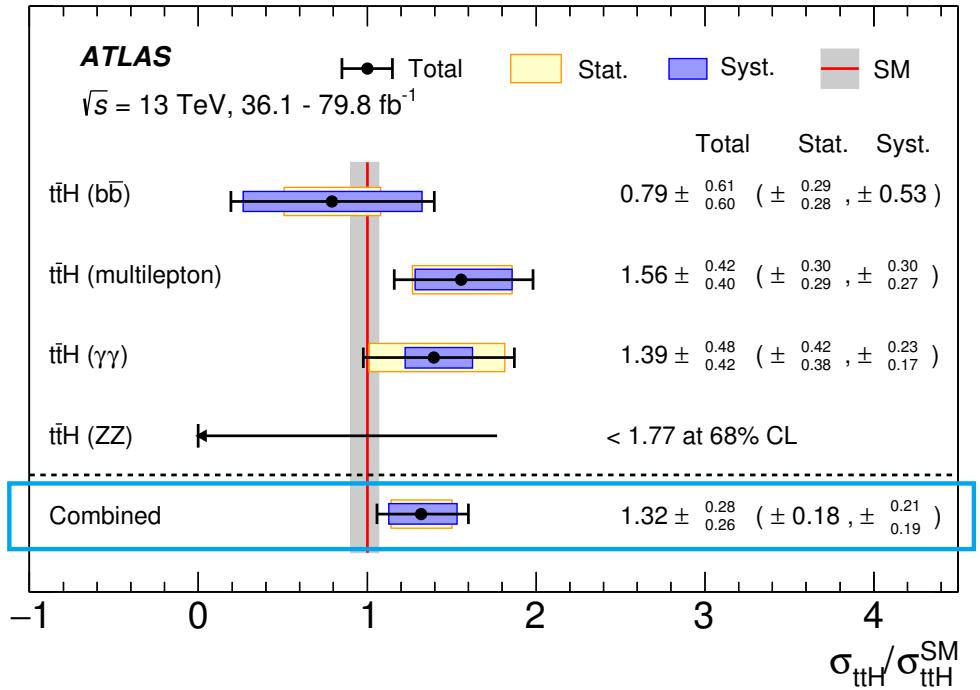


Observation of $t\bar{t}H$ production

Combination of $t\bar{t}H$ searches in ATLAS and CMS

CMS

Parameter	Best fit	Uncertainty: Stat	Expt	Thbgd	Thsig
$\mu_{t\bar{t}H}^{7+8\,\mathrm{TeV}}$	$2.59^{+1.01}_{-0.88}$	$^{+0.54}_{-0.53}$	$^{+0.53}_{-0.49}$	$^{+0.55}_{-0.49}$	$^{+0.37}_{-0.13}$
	$\left(^{+0.87}_{-0.79}\right)$	$\left(^{+0.51}_{-0.49}\right)$	$\left(^{+0.48}_{-0.44}\right)$	$\left(^{+0.50}_{-0.44}\right)$	$\left(^{+0.14}_{-0.02}\right)$
$\mu_{t\bar{t}H}^{13\,\mathrm{TeV}}$	$1.14^{+0.31}_{-0.27}$	$^{+0.17}_{-0.16}$	$^{+0.17}_{-0.17}$	$^{+0.13}_{-0.12}$	$^{+0.14}_{-0.06}$
	$\left(^{+0.29}_{-0.26}\right)$	$\left(^{+0.16}_{-0.16}\right)$	$\left(^{+0.17}_{-0.16}\right)$	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.11}_{-0.05}\right)$
$\mu_{t\bar{t}H}$	$1.26^{+0.31}_{-0.26}$	$^{+0.16}_{-0.16}$	$^{+0.17}_{-0.15}$	$^{+0.14}_{-0.13}$	$^{+0.15}_{-0.07}$
	$\left(^{+0.28}_{-0.25}\right)$	$\left(^{+0.15}_{-0.15}\right)$	$\left(^{+0.16}_{-0.15}\right)$	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.11}_{-0.05}\right)$



- combined signal strength compatible with SM (uncertainty of $\sim 20\%$)
- Next slides: a closer look at multilepton and $H \to b\bar{b}$ analyses
  - channels with largest systematic uncertainties

Observation of $t\bar{t}H$ production

Combination of $t\bar{t}H$ searches in ATLAS and CMS

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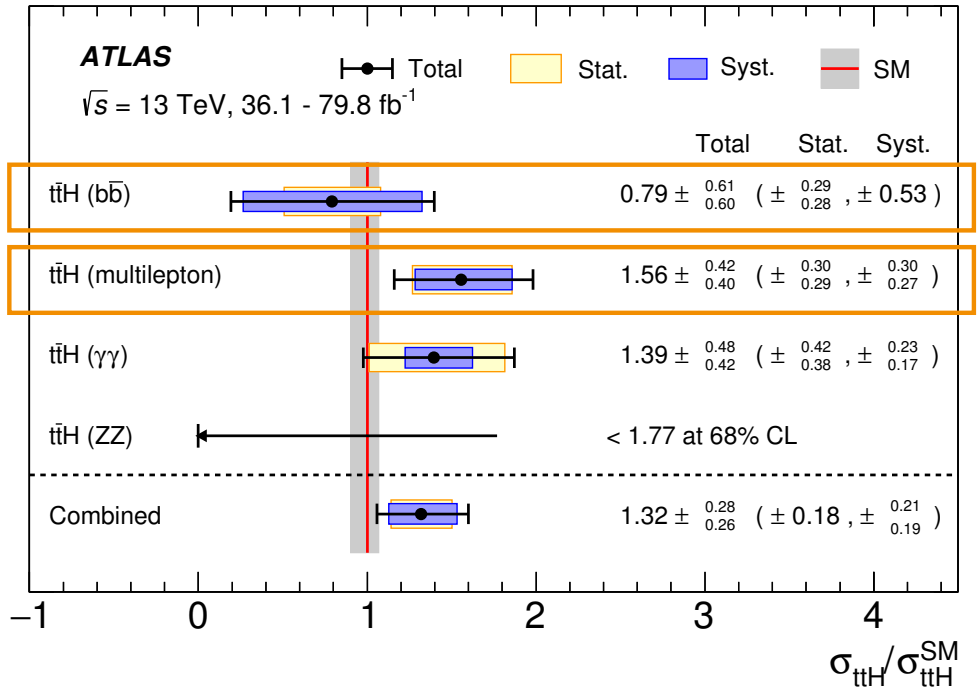
$\mu_{t\bar{t}H}^{13\,\mathrm{TeV}}$	$1.14^{+0.31}_{-0.27}$	$^{+0.17}_{-0.16}$	$^{+0.17}_{-0.17}$	$^{+0.13}_{-0.12}$	$^{+0.14}_{-0.06}$
	$\left(^{+0.29}_{-0.26}\right)$	$\left(^{+0.16}_{-0.16}\right)$	$\left(^{+0.17}_{-0.16}\right)$	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.11}_{-0.05}\right)$
$\mu_{t\bar{t}H}$	$1.26^{+0.31}_{-0.26}$	$^{+0.16}_{-0.16}$	$^{+0.17}_{-0.15}$	$^{+0.14}_{-0.13}$	$^{+0.15}_{-0.07}$
	$\left(^{+0.28}_{-0.25}\right)$	$\left(^{+0.15}_{-0.15}\right)$	$\left(^{+0.16}_{-0.15}\right)$	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.11}_{-0.05}\right)$



- combined signal strength compatible with SM (uncertainty of $\sim 20\%$)
- Next slides: a closer look at multilepton and $H \to b\bar{b}$ analyses
  - channels with largest systematic uncertainties

$t\bar{t}H$ with $H \to b\bar{b}$

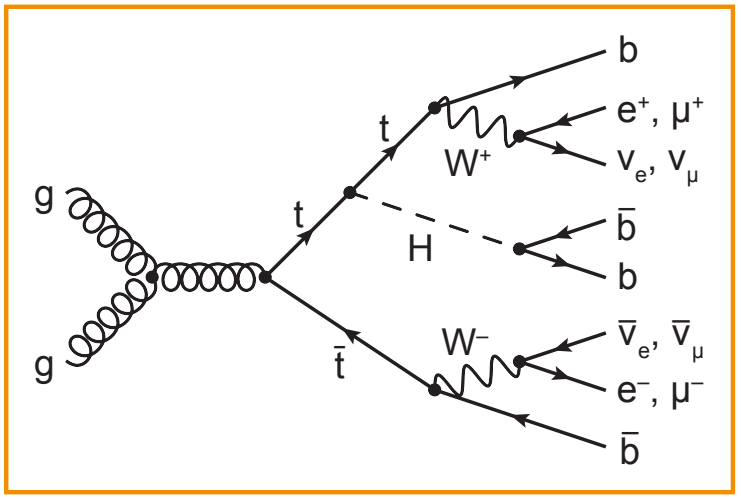
ATLAS : HIGG-2017-03, Phys. Rev. D 97 (2018) 072016

CMS : HIG-17-022, JHEP 06 (2018) 101

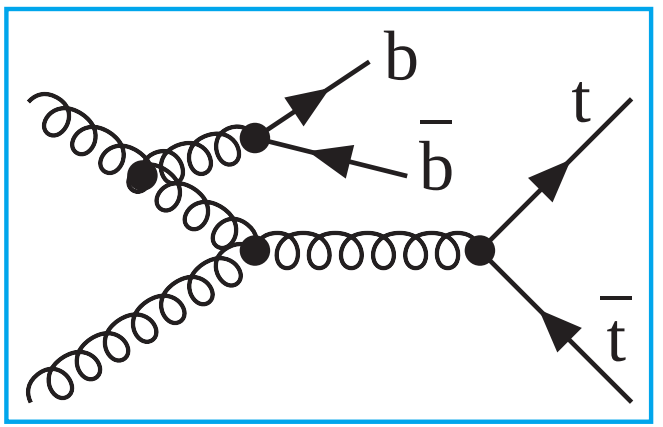
HIG-17-026, JHEP 03 (2019) 026

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

- final states with up to 4 b-jets
  - 0, 1 or 2 leptons from $t\bar{t}$ decay
- large $t\bar{t}$ + jets bkg, incl. irreducible $t\bar{t} + b\bar{b}$
- background model based on MC
  - $t\bar{t}$ + jets MC: Powheg+Pythia8
  - dedicated uncert. assigned to $t\bar{t} + \mathrm{hf}$
- final discriminants based on MVA methods
  - $H(b\bar{b})$ reco hindered by (b-)jets combinatorics
- next slides: will focus on 1ℓ and 2ℓ analyses
  - CMS also performed a dedicated fully-hadronic analysis [BACKUP]



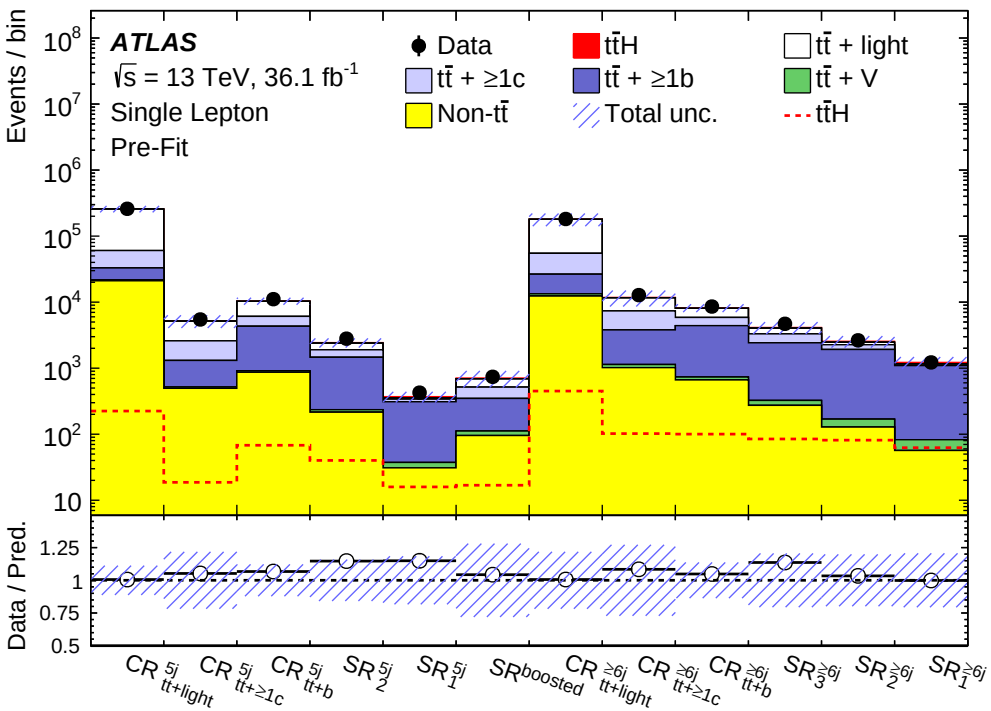
$t\bar{t}H(\to b\bar{b})$	0.3 pb
$t\bar{t} + b\bar{b}$	4 pb
$t\bar{t}$	832 pb

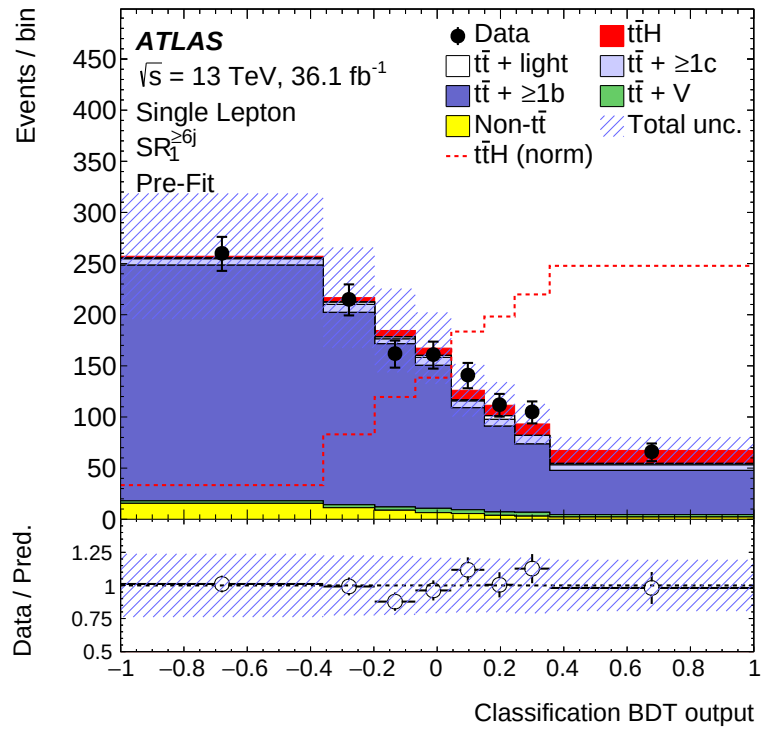


$t\bar{t}H(\to b\bar{b})$ [ATLAS]

Categories and S/B discriminants in 1ℓ and 2ℓ channels

- SRs and CRs based on N_{jets} and b-tag purity (4 b-tag Working Points)
- final discriminants in each SR: classification BDT ($t\bar{t}H$ vs $t\bar{t}$)

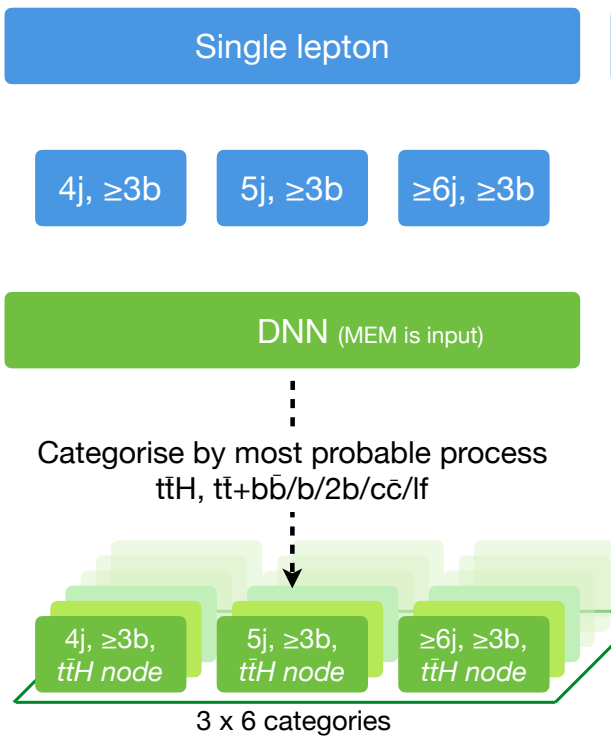


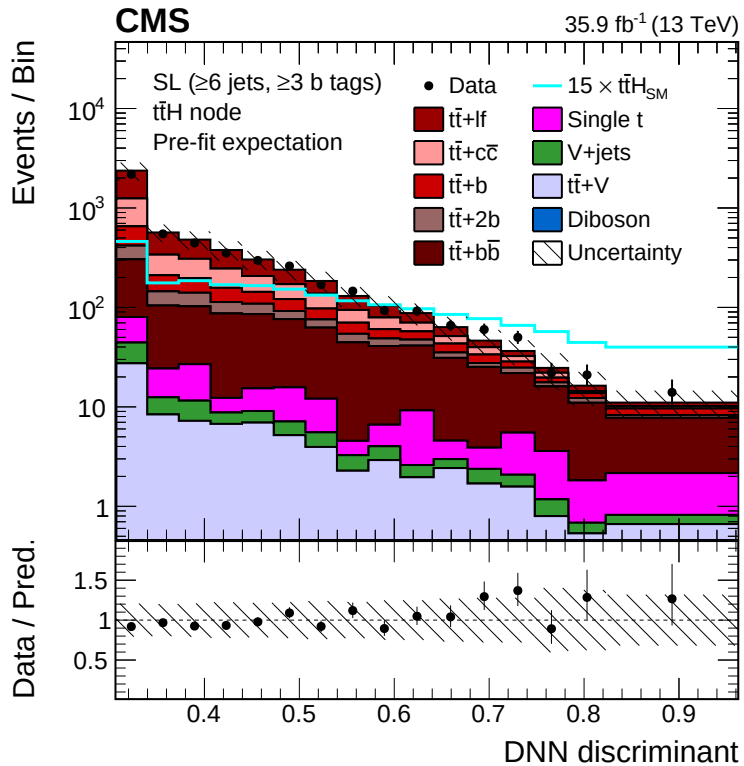


$t\bar{t}H(\to b\bar{b})$ [CMS]

Categories and S/B discriminants in 1ℓ and 2ℓ channels

- categories based on N_{jets} and $N_{\text{b-tags}}$ (1 b-tag WP)
- 2ℓ channel: BDT optimized independently for each SR
- 1ℓ channel: multi-class DNN used to define sub-categories enriched in $t\bar{t}+\text{lf}$, $t\bar{t}+c\bar{c}$, $t\bar{t}+b$, $t\bar{t}+2b$, $t\bar{t}+b\bar{b}$ and $t\bar{t}H$





$t\bar{t}H(\to b\bar{b})$: $t\bar{t}+\mathrm{hf}$ modeling

Nominal prediction, systematics and fit model validation

- $t\bar{t}+$ jets MC: Powheg+Pythia8 (NNPDF3.0), normalized to NNLO+NNLL
- split in $t\bar{t}+b\bar{b}$, $t\bar{t}+2b$, $t\bar{t}+b$, $t\bar{t}+c\bar{c}$, $t\bar{t}+\mathrm{lf}$ based on flavor content of particle-level jets

[More details in BACKUP]

ATLAS

- $t\bar{t}+\geqslant 1b, 1c$ normalizations free-floating
- shapes unc. from several generator-comparison systematics:
  - Nominal vs SHERPA-5FS, vs HERWIG-7 (PS and hadroniz.)
  - $t\bar{t}+\geqslant 1b$: Nomi. vs Sherpa-4FS
  - $t\bar{t}+\geqslant 1c$: 5FS vs 3FS ($c\bar{c}$ from ME)
- ISR/FSR: varied $\mu_{\mathrm{R/F}}$, h_{damp} and Tune
- fit model validation (no bias in $\mu_{t\bar{t}H}$):
  - fits to pseudo-data from POWHEG+PY6

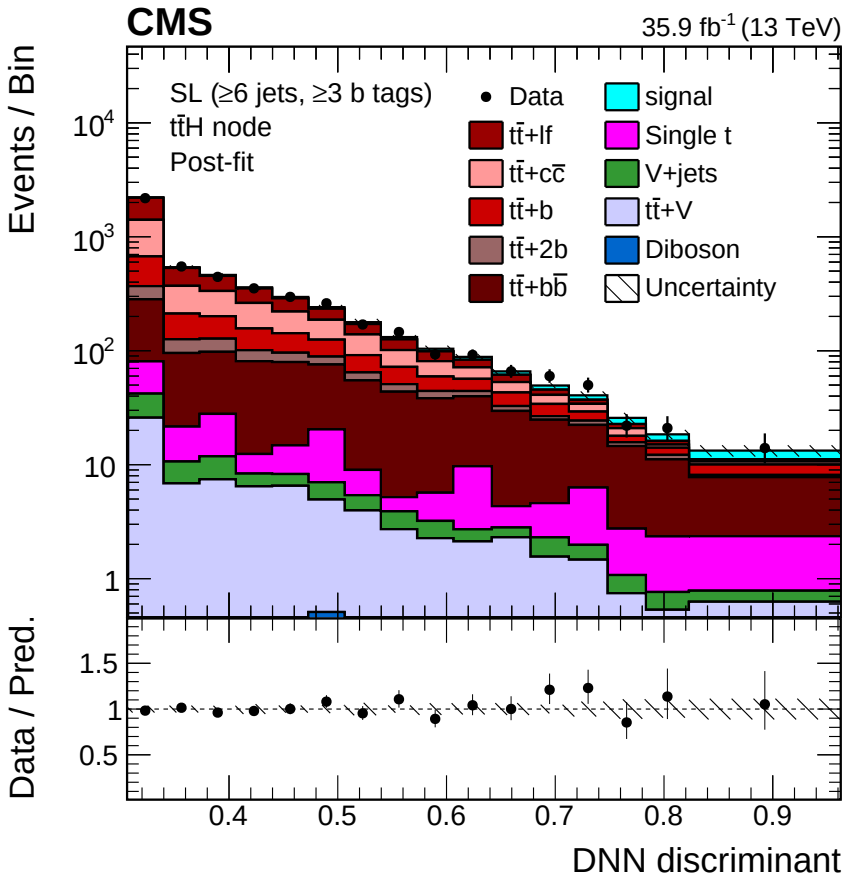
CMS

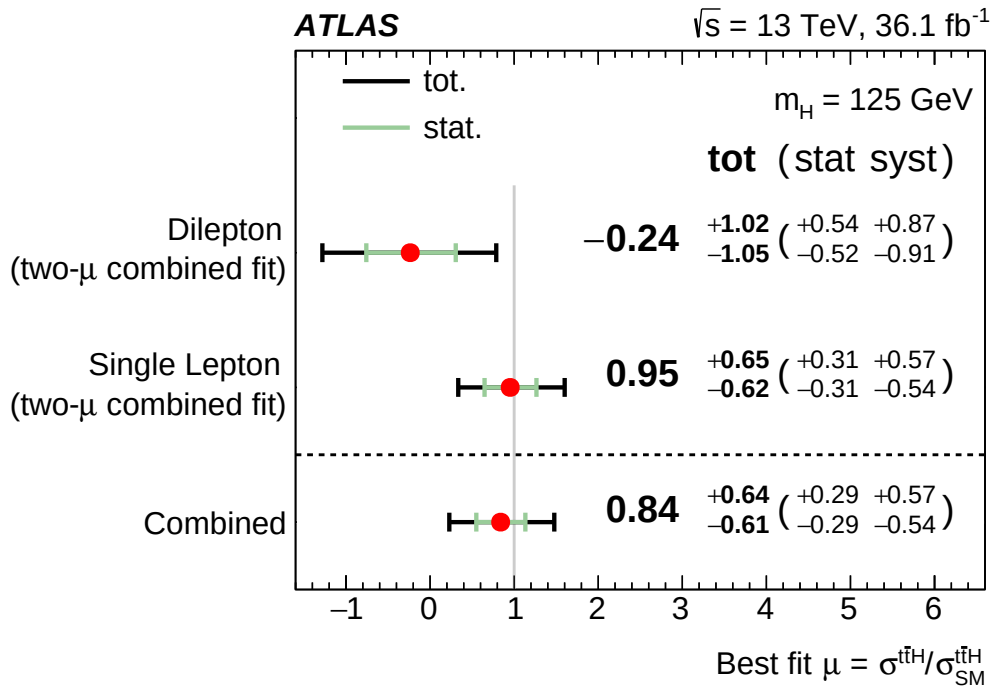
- independ. norms for all 5 $t\bar{t}+jj$ processes
  - 50% priors for $t\bar{t}+b\bar{b}$, $2b$, b, $c\bar{c}$ norms
- additional syst. from PDF, $\mu_{\mathrm{R/F}}$ scales, ISR/FSR, Tune and h_{damp} (last 3: uncorrelated between $t\bar{t}+\mathrm{hf}$ procs)
- fit model validation (no bias in $\mu_{t\bar{t}H}$):
  - varied priors on $t\bar{t}+\mathrm{hf}$ norms
  - free-floating $t\bar{t}+b\bar{b}$ norm
  - fits to pseudo-data with $+30\%$ $t\bar{t}+b\bar{b}$ rate, or based on Sherpa-4FS $t\bar{t}+b\bar{b}$

$t\bar{t}H(\rightarrow b\bar{b})$: results

Post-fit discriminants and $t\bar{t}H$ signal strength

- excess compatible with SM $t\bar{t}H$
- Obs. significance: 1.4σ (ATLAS), 1.6σ (CMS)





$t\bar{t}H(\to b\bar{b})$: post-fit uncertainties

Breakdown of dominant systematic uncertainties

- largest systematic uncertainties on $\mu_{t\bar{t}H}$ from
  - $t\bar{t}+\text{hf}$ modeling, $t\bar{t}H$ cross section unc.
  - b-tagging efficiency, jet energy scale
  - size of MC samples

ATLAS

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

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	$+0.45/-0.45$	$+0.53/-0.49$

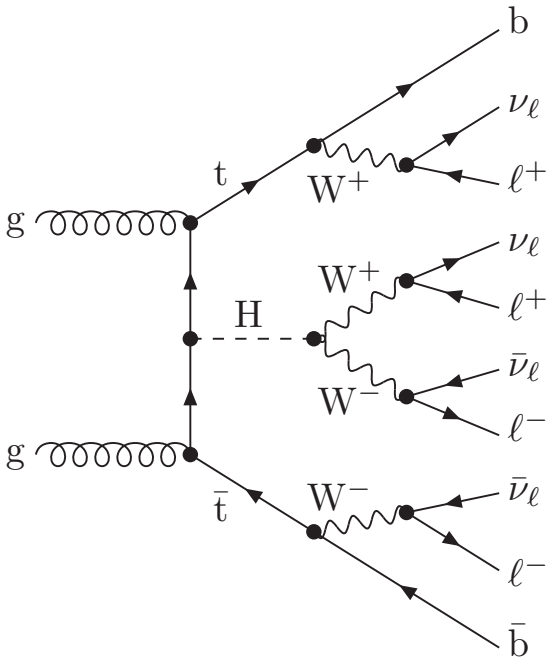
$t\bar{t}H \rightarrow$ multilepton

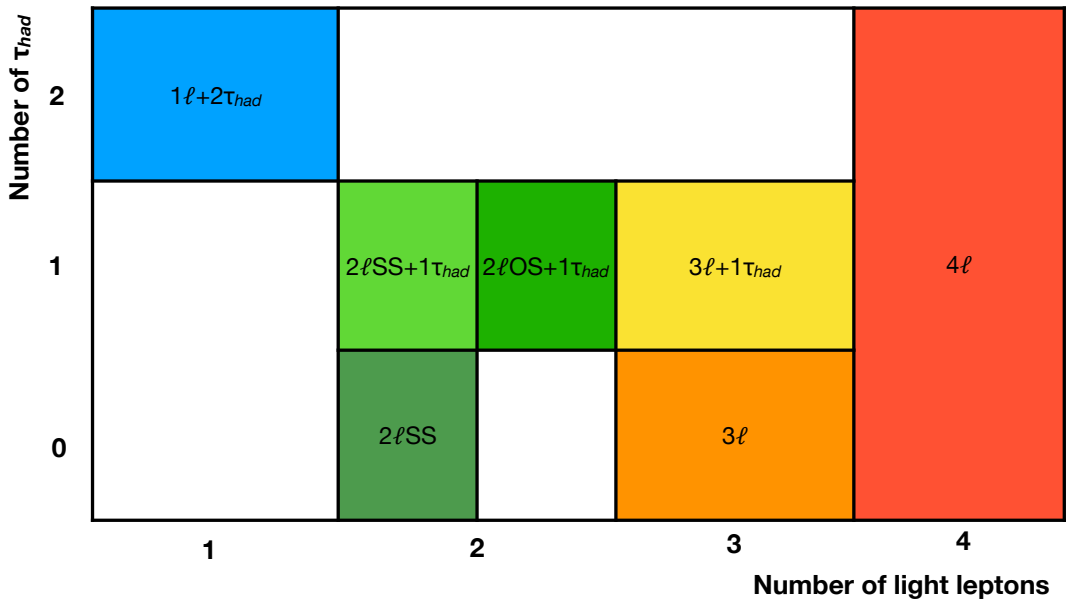
ATLAS : HIGG-2017-02, Phys. Rev. D 97 (2018) 072003

CMS : HIG-18-019

$t\bar{t}H$ multilepton

- targets $H \to WW^*, ZZ^*, \tau^+\tau^-$ decays
- categories defined by number of light leptons and τ_{h} with categ-dependent requirements on N_{jets} and $N_{\text{b-tags}}$

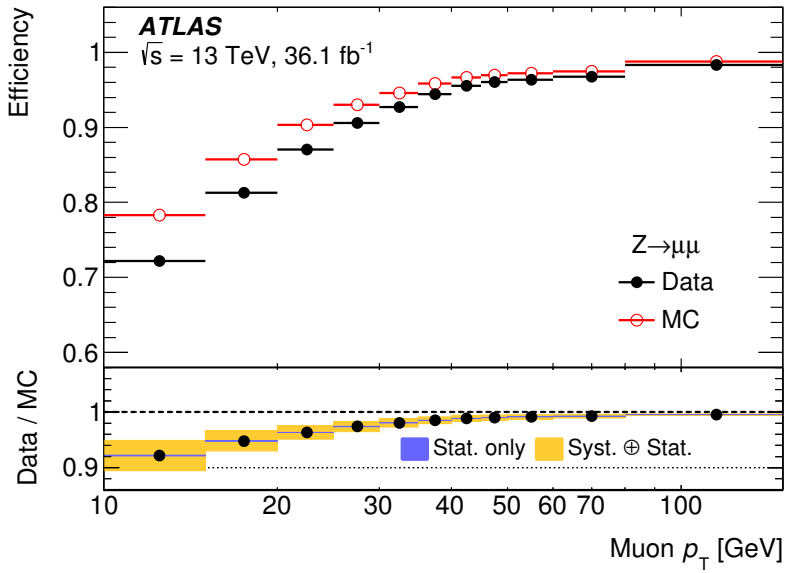




highest sensitivity : 2ℓ same-sign (SS) and 3ℓ categories

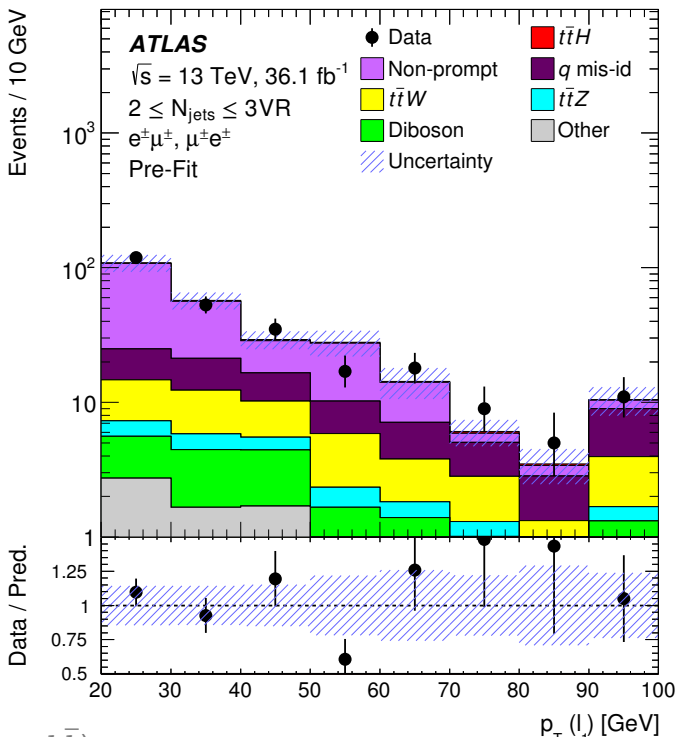
main bkgs : $t\bar{t}W$, $t\bar{t}Z$ and fake/non-prompt ℓ ($t\bar{t}$ + jets)

$t\bar{t}H$ multilepton : ℓ ID and fake/non-prompt ℓ bkg



- dedicated BDT-based lepton-ID
  - based on properties of energy deposits and tracks reconstructed around lepton
  - used to reject non-prompt leptons retaining high signal efficiency

- fake and non-prompt lepton bkg ($t\bar{t}$ + jets) determined from data:
  - based on measur. of ℓ-mistag rates for e / μ / τ_{h} wrt lepton kinematics
  - incl. estimate of bkgs from charge-misID and $\gamma \to e^+e^-$ conversions

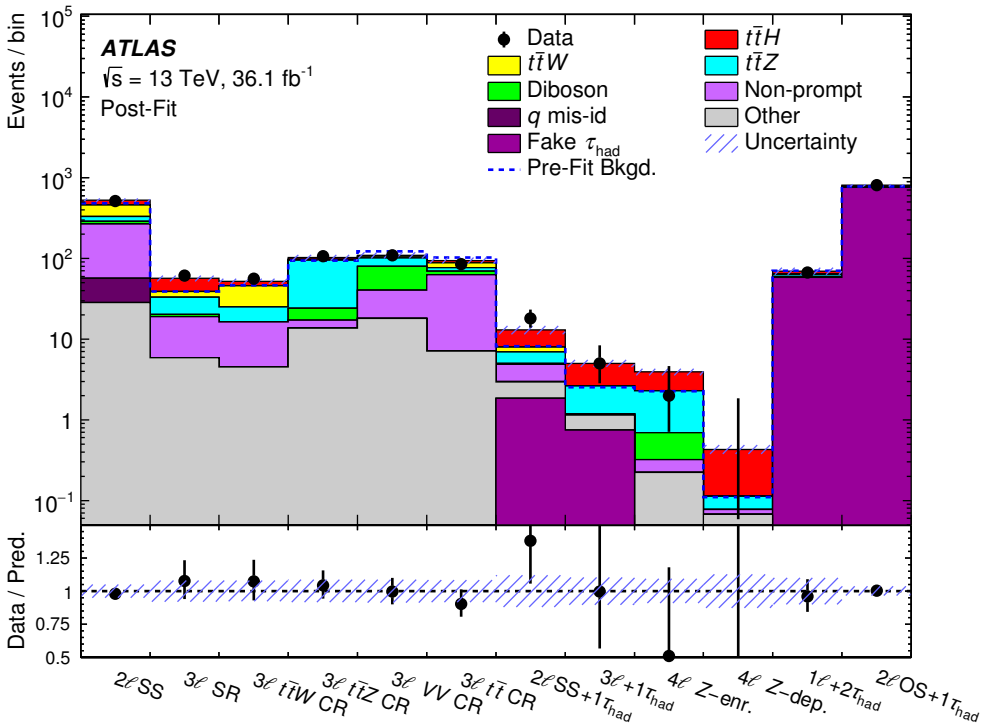


$t\bar{t}H$ multilepton : $t\bar{t}V$ modeling and event yields

- $t\bar{t}W$ and $t\bar{t}Z$ bkgs constrained using dedicated CRs
  (e.g. Z-mass cut for $t\bar{t}Z$, low N-jet for $t\bar{t}W$)
  - MC: MG5_aMC@NLO + Pythia8

[ATLAS] $t\bar{t}V$ xsecs (and priors) from theory + comparison to alt. NLO ME (Sherpa)

[CMS] $t\bar{t}V$ normalizations free-floating in final fit + shape unc. from MC



CMS

[post-fit yields of selected categories]

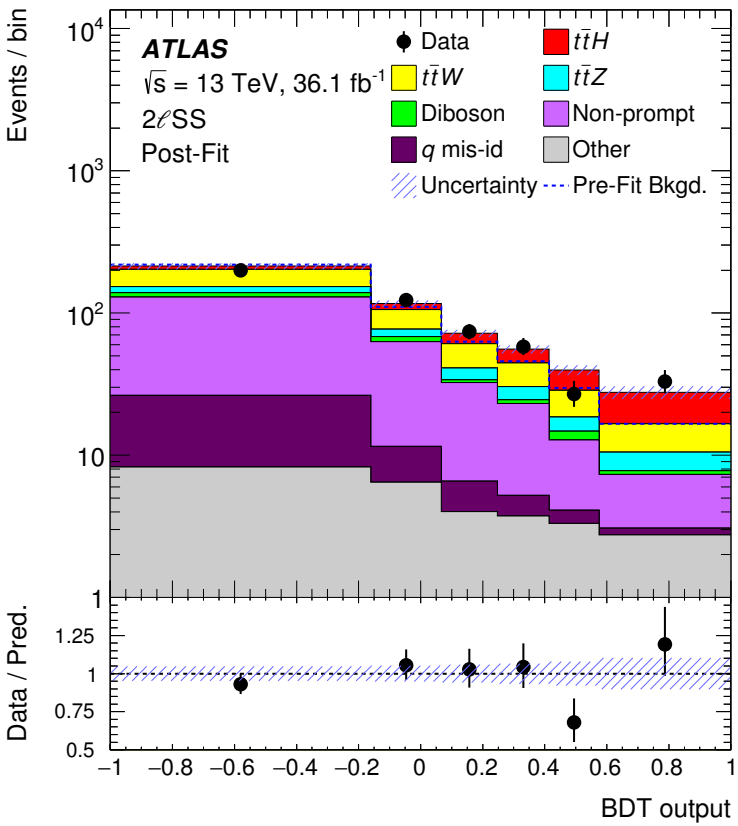
Category	$2\ell ss$	3ℓ	4ℓ
$t\bar{t}H$	43.0 ± 7.1	18.8 ± 4.8	0.7 ± 0.3
$t\bar{t}W + t\bar{t}WW$	218.5 ± 13.7	51.0 ± 5.3	0.13 ± 0.03
tH	2.4 ± 0.1	0.9 ± 0.1	< 0.05
$WZ + ZZ$	< 0.05	12.0 ± 1.7	0.15 ± 0.10
$t\bar{t}Z/\gamma^*$	138.2 ± 7.6	74.1 ± 6.3	3.9 ± 0.6
Misidentified	132.1 ± 10.0	26.8 ± 4.0	< 0.05
Conversions	11.6 ± 3.0	6.6 ± 1.3	< 0.05
Signal flip	22.8 ± 2.3	< 0.05	< 0.05
Other	26.7 ± 3.9	9.7 ± 2.2	< 0.05
SM expectation	595.3 ± 20.6	200.0 ± 10.8	5.0 ± 0.7
Observed data	614	195	6

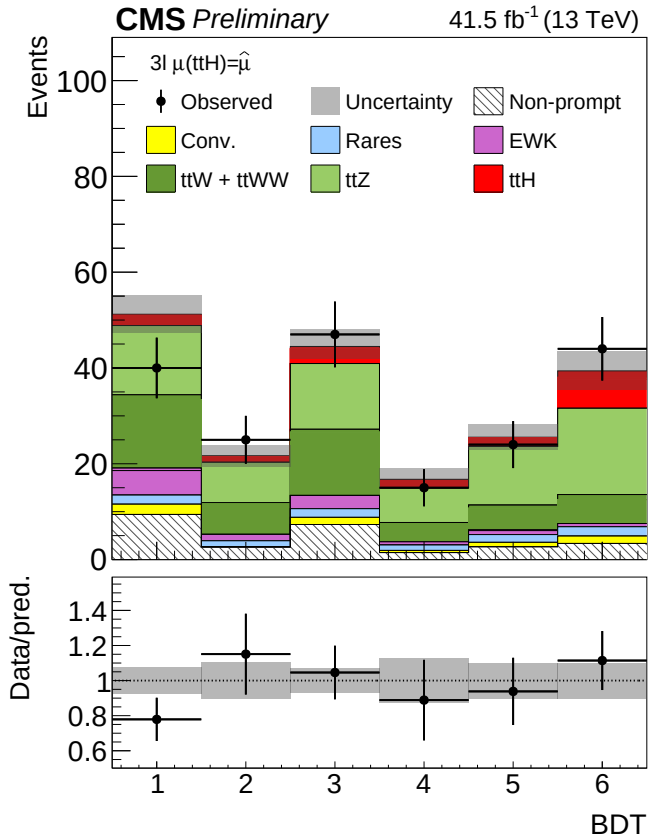
$t\bar{t}H$ multilepton : post-fit discriminants

- SR discriminants based on BDT outputs
  (only yields used in categs with low-stats, e.g. 4ℓ)

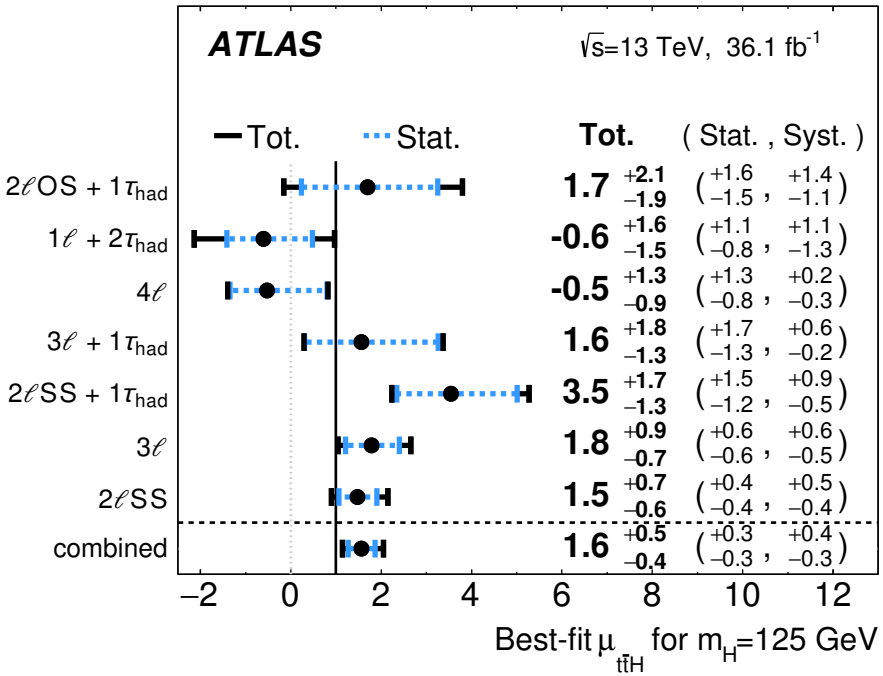
[2ℓSS and CMS-3ℓ] separate BDTs trained for ($t\bar{t}H$ vs $t\bar{t}$, $t\bar{t}V$), combined into 1D dist.

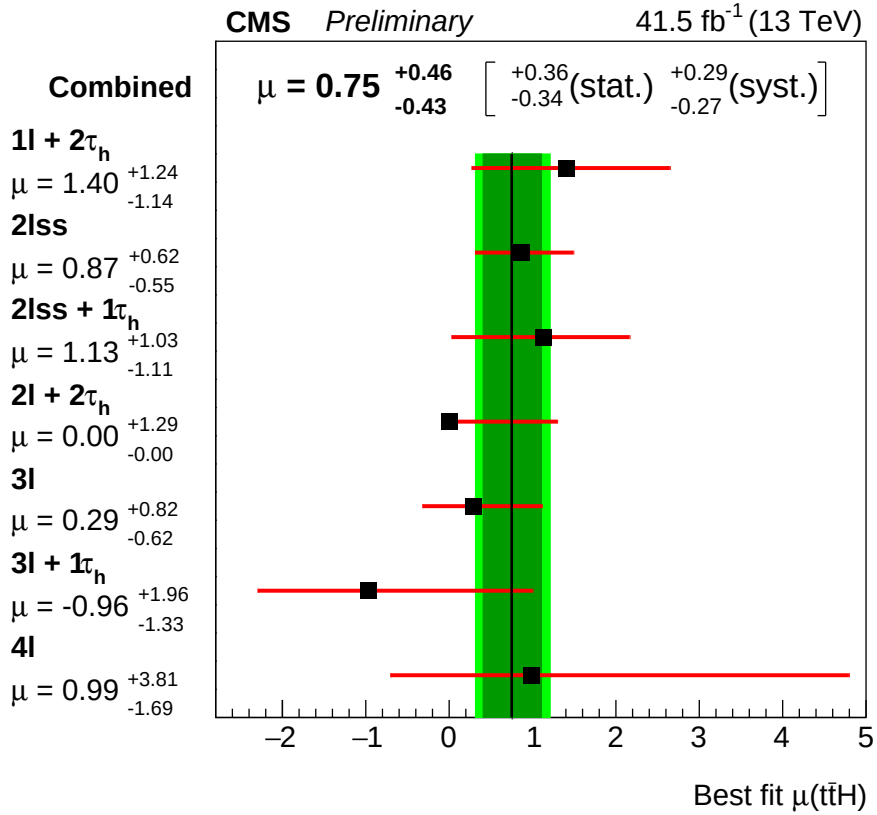
[ATLAS-3ℓ] multi-class BDT (5 processes: $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}$, VV)





$t\bar{t}H$ multilepton : results





$\mu_{t\bar{t}H}$ in agreement with SM

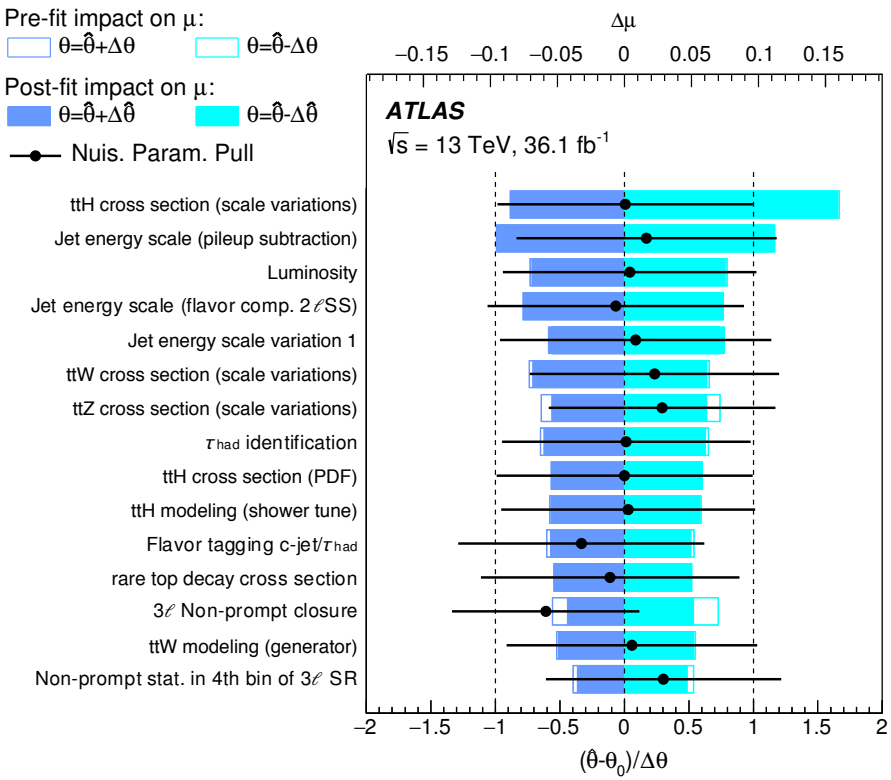
- evidence of $t\bar{t}H \rightarrow$ multilepton reached by both experiments
- syst. and stat. uncs of comparable size for the 2 most sensitive sub-channels (2ℓSS and 3ℓ)

$t\bar{t}H$ multilepton	Obs (Exp) Signif.	
ATLAS (2016)	4.1σ	(2.8σ)
CMS (2017)	1.7σ	(2.9σ)
CMS (2016+2017)	3.2σ	(4.0σ)

$t\bar{t}H$ multilepton : post-fit uncertainties

Breakdown of dominant systematic uncertainties

- largest systematic uncertainties on $\mu_{t\bar{t}H}$ from
  - fake/non-prompt ℓ bkg
  - $t\bar{t}V$ modeling, $t\bar{t}H$ cross section unc.
  - b-tagging eff., jet energy calibration, $e/\mu/\tau_{\mathrm{h}}$ eff.



CMS

Source	Uncertainty [%]	$\Delta\mu/\mu$ [%] (2017)
Theoretical sources	≈ 8	8
e, μ selection efficiency	3–5	4
τ_{h} selection efficiency	5	3
τ_{h} energy calibration	1.2	1
b tagging efficiency	2–15 [48]	10
Jet energy calibration	2–15 [56]	3
Fake background yield	$\approx$ 30–50	17

tH

CMS : HIG-17-005 (multilepton)

HIG-17-016 ($H \to b\bar{b}$)

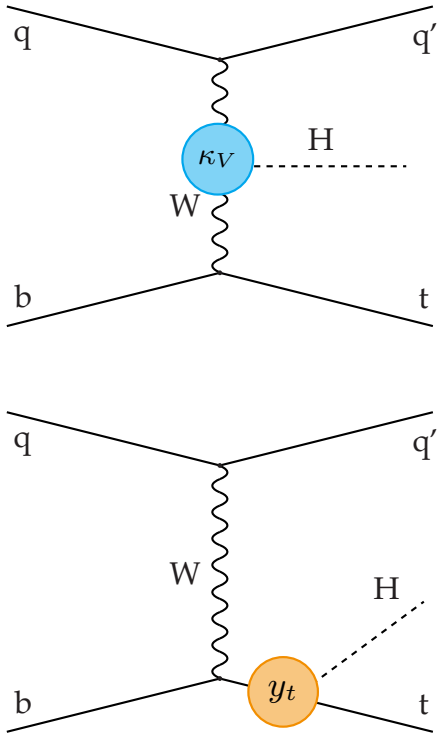
HIG-18-009 (combination), submitted to Phys. Rev. D

tH production

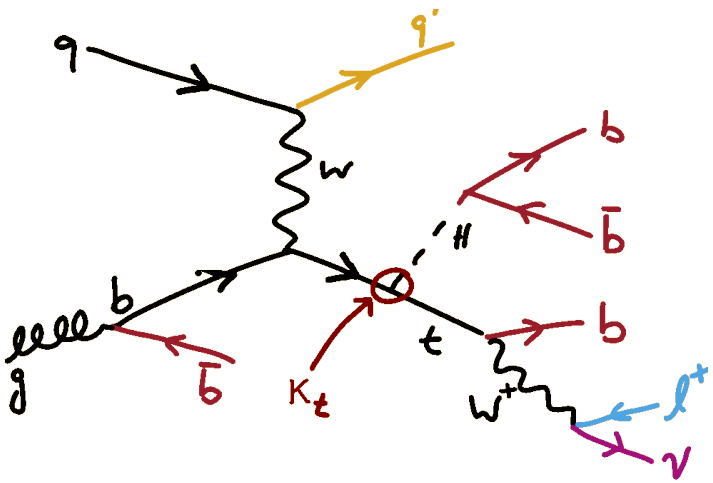
- tH production: tHq and tHW
  - depends on Higgs couplings to both top and gauge bosons
  - interf. effects make it sensitive to relative sign of y_t and g_{HVV}. For $\kappa_V = 1$:

SM ($y_t = +1$) : low xsec (~ 0.1 pb) due to destructive interf.

ITC ($y_t = -1$) : xsec $\times 10$ higher wrt SM



- **CMS** has performed dedicated searches for tH production in multilepton and $H \to b\bar{b}$ channels using 2016 data
  - analysis methods (obj-reco, bkg model) similar to the corresponding $t\bar{t}H$ analyses



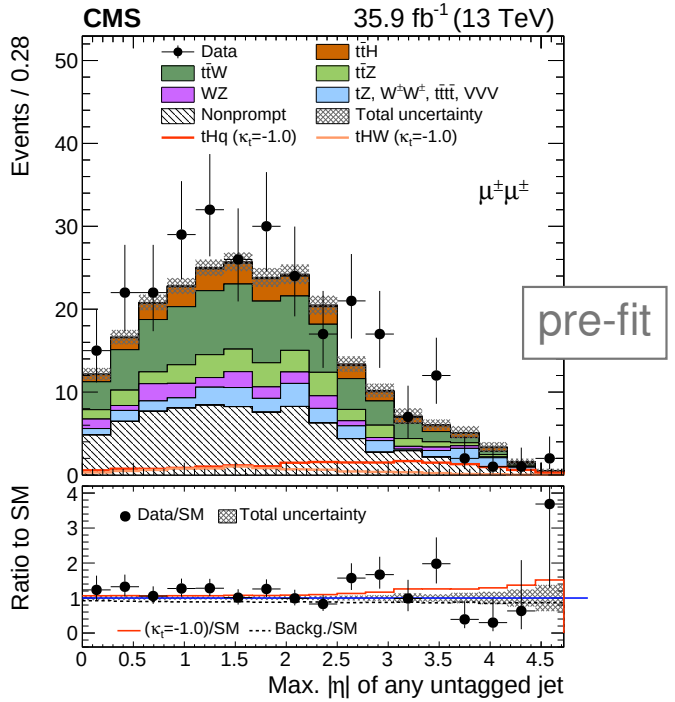
tH multilepton

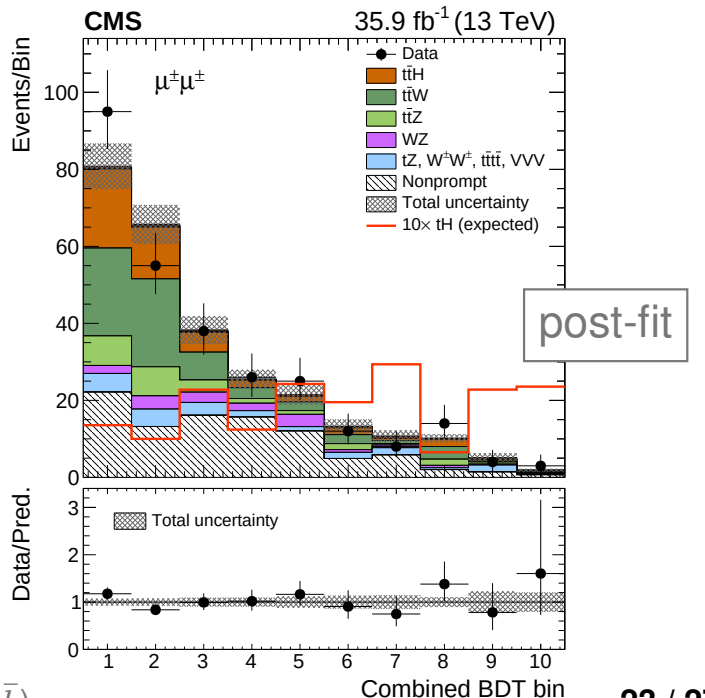
HIG-18-009, HIG-17-005

- 3 channels: $\mu^{\pm}\mu^{\pm}$, $e^{\pm}\mu^{\pm}$ and 3ℓ
  - 1 b-jet + 1 forward jet in final state
- Signal yield:
  - tH SM (ITC) $\sim 1\%(10\%)$ wrt SM bkg
- final discriminant in each SR:

  1D dist. based on 2 BDT outputs

  [tHq vs $t\bar{t}V$], and [tHq vs $t\bar{t}$], inputs:
  - forward jet activity
  - jet and b-jet multiplicities
  - leptons' kinematics
- bkg model and dominant systematics very similar to $t\bar{t}H$ multilepton



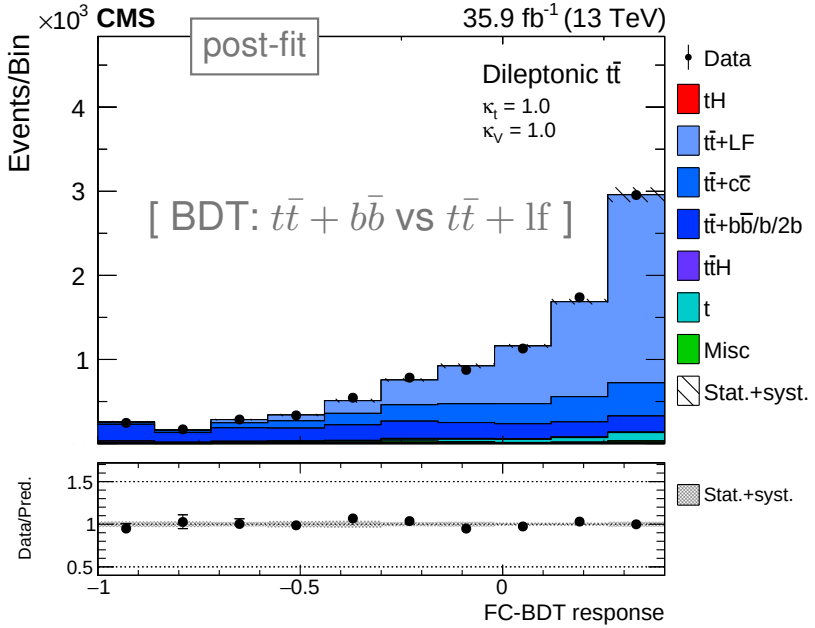


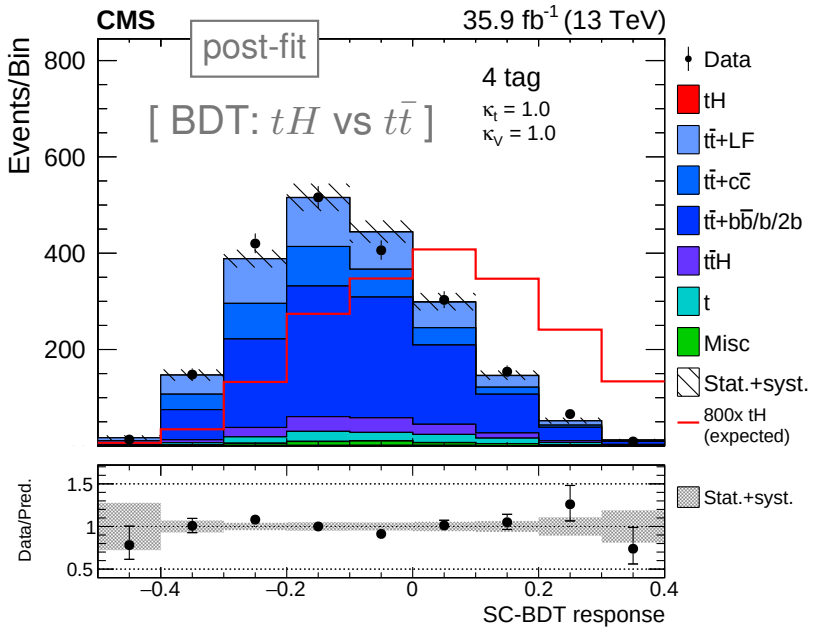
tH with $H \to b\bar{b}$

HIG-18-009, HIG-17-016

1ℓ + MET + $\geqslant 3$ b-jets + 1 forward-jet

- large $t\bar{t}$ + jets bkg (from MC)
- BDT-based kinem. reconstruction of tHq, tHW and $t\bar{t}$ hypotheses
  (jet-parton assignment)
- 3b and 4b SRs: BDT [tH vs $t\bar{t}$]
  Inputs: obj-kinem. and reco-BDT vars
- $\ell^{\pm}\ell'^{\mp}$ CR: BDT [$t\bar{t} + b\bar{b}$ vs $t\bar{t} + \mathrm{lf}$]
  used to constrain $t\bar{t} + \mathrm{hf}$ bkgs
- bkg model and dominant systematics very similar to $t\bar{t}H(b\bar{b})$ analysis



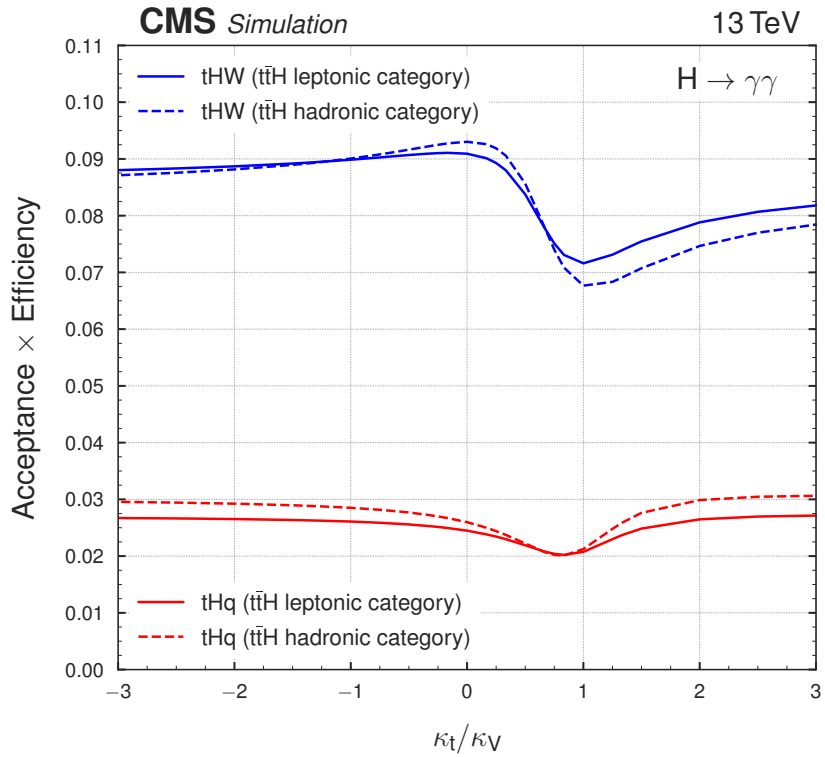


tH combination : inputs

HIG-18-009

- tH combination:
  - multilepton and $H \to b\bar{b}$ channels
  - re-interpretation of the $t\bar{t}H$ categories of the $H \to \gamma\gamma$ analysis

- $H \to \gamma\gamma$ decay sensitive as well to relative sign of y_t and g_{HVV} couplings
- expected yields of $tH(\gamma\gamma)$ signals parameterized wrt ratio of coupling modifiers



tH combination : results

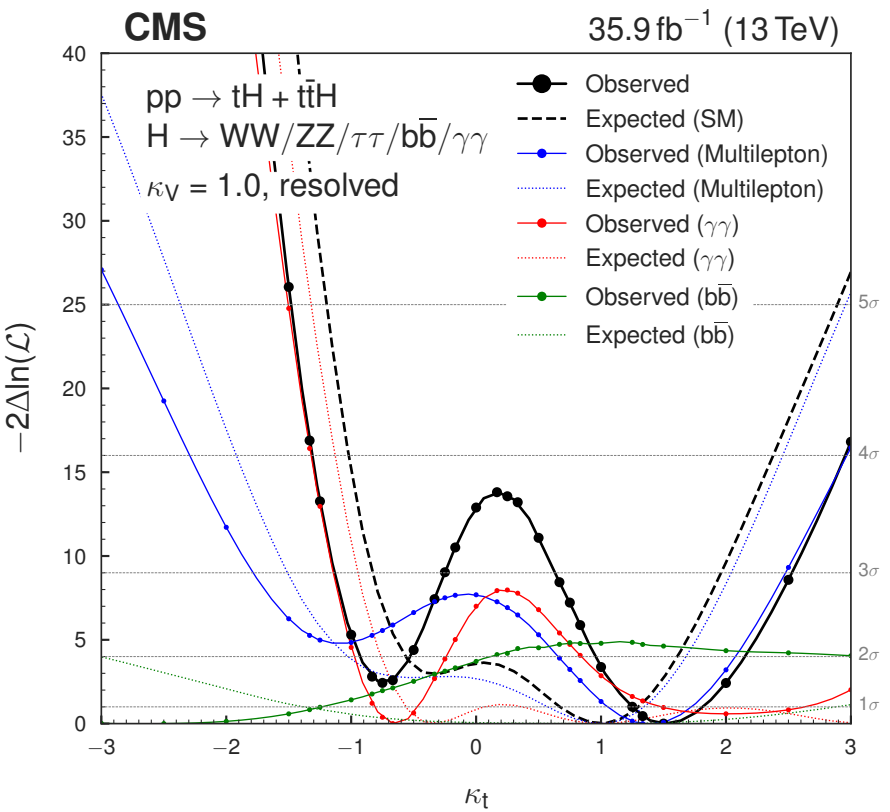
HIG-18-009

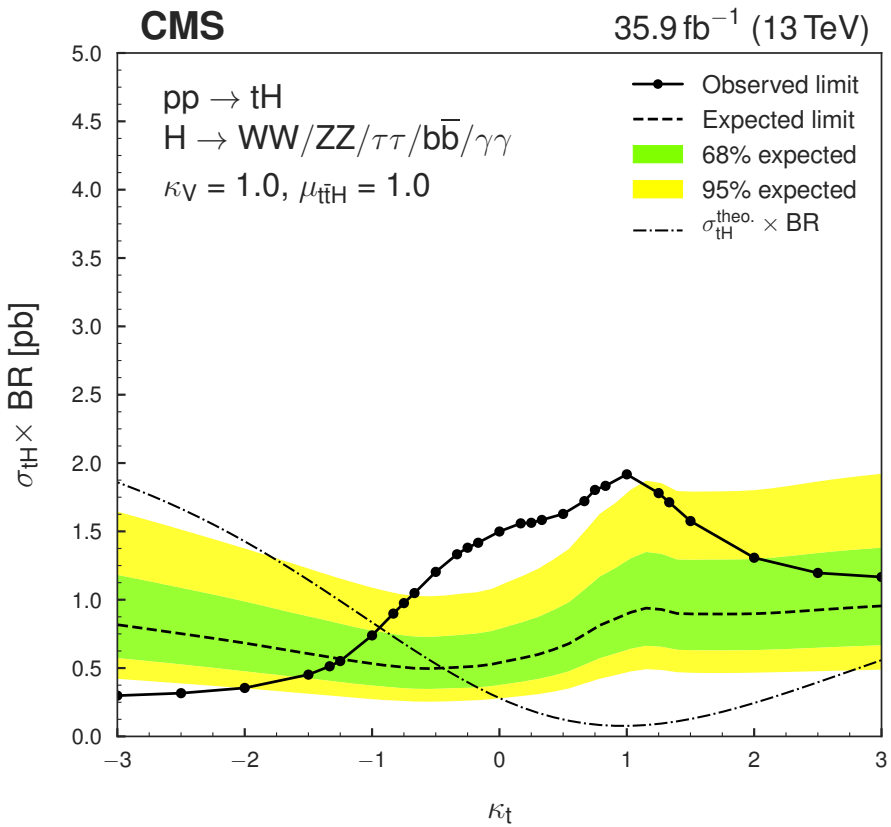
Likelihood scan with respect to κ_t ($\kappa_V = +1$):

- positive κ_t favored over negative value by 1.5σ
- y_t values outside of $[-0.9, -0.5]$ and $[1.0, 2.1]$ excluded at 95% CL

95% CL UL on $\sigma_{tH} \times$ BR ($\kappa_V = +1$):

- $t\bar{t}H$ yield fixed to SM (κ_t-dep.)
- Obs (Exp) UL for $y_t = +1$: $25(12) \times$ SM





Summary

- top-Higgs coupling has been directly established at the LHC
  - $t\bar{t}H$ signal strength measured with $\sim 20\%$ uncertainty (per experiment) and compatible with SM
  - multilepton and $b\bar{b}$ analyses:
    - sensitivity will still improve with more data and refinement of analysis techniques (e.g. b-tagging for $t\bar{t}H(b\bar{b})$), but systematic unc. are already significant for these channels
    - improvements to modeling of irreducible backgrounds and signal will be important to push the envelope in these channels
- tH production: dedicated searches in multilepton and $H \to b\bar{b}$ channels
  - analyses impacted by similar systematics as $t\bar{t}H$ counterparts
  - under certain assumptions ($\kappa_V = 1$ and resolved $H\gamma\gamma$ loop), latest CMS tH combination excludes $y_t = -1$ at 95% CL

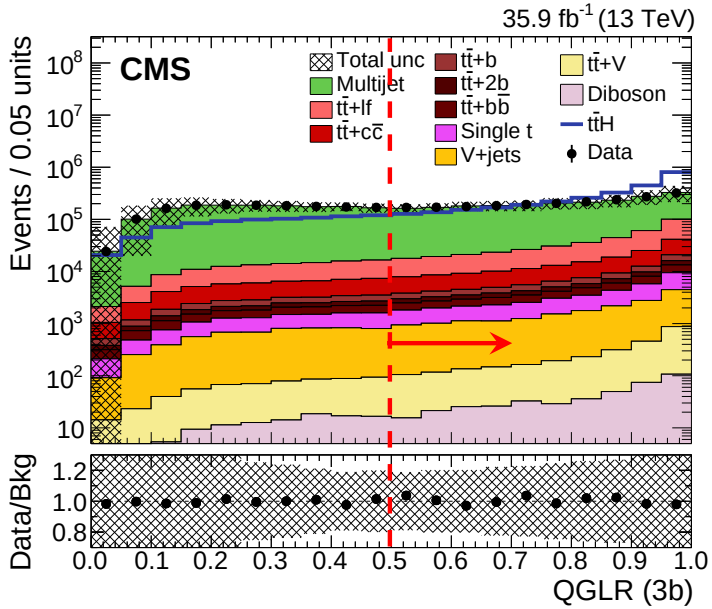
BACKUP

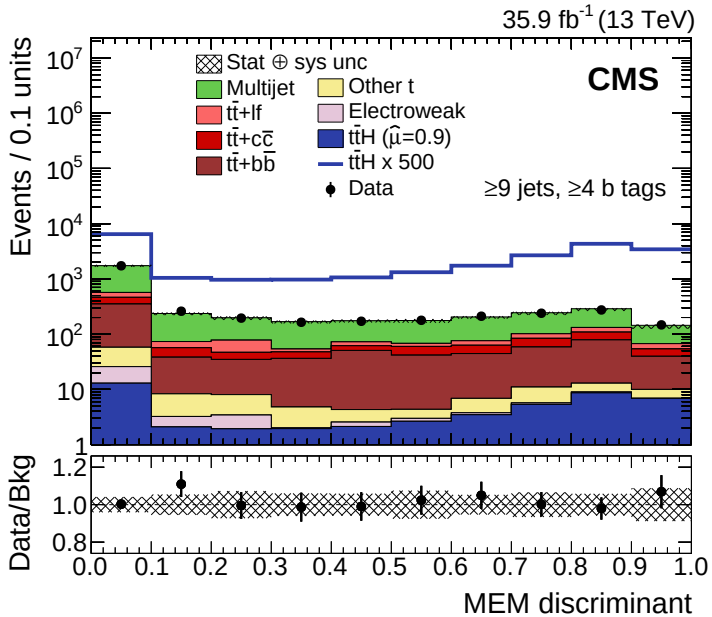
$t\bar{t}H(\to b\bar{b})$ in the fully-hadronic final state

HIG-17-022

- highest $t\bar{t}H$ BR, but huge QCD multijet bkg
- events with $\geqslant 7$ jets and $\geqslant 3$ b-jets
  - 6 categ based on # of jets and b-jets
- quark-gluon jet tagger to reduce QCD bkg
- data-driven QCD bkg (2b CR)
- final discriminant: Matrix Element Method, designed to separate $t\bar{t}H$ and $t\bar{t}+b\bar{b}$
- sensitivity limited by systematics
  - data-driven QCD bkg, b-tagging, jes

Obs. (Exp.) upper limit: $\mu_{95\%} < 3.8\,(3.1)$





$t\bar{t}H(\to b\bar{b})$: $t\bar{t}+\mathrm{hf}$ modeling [ATLAS]

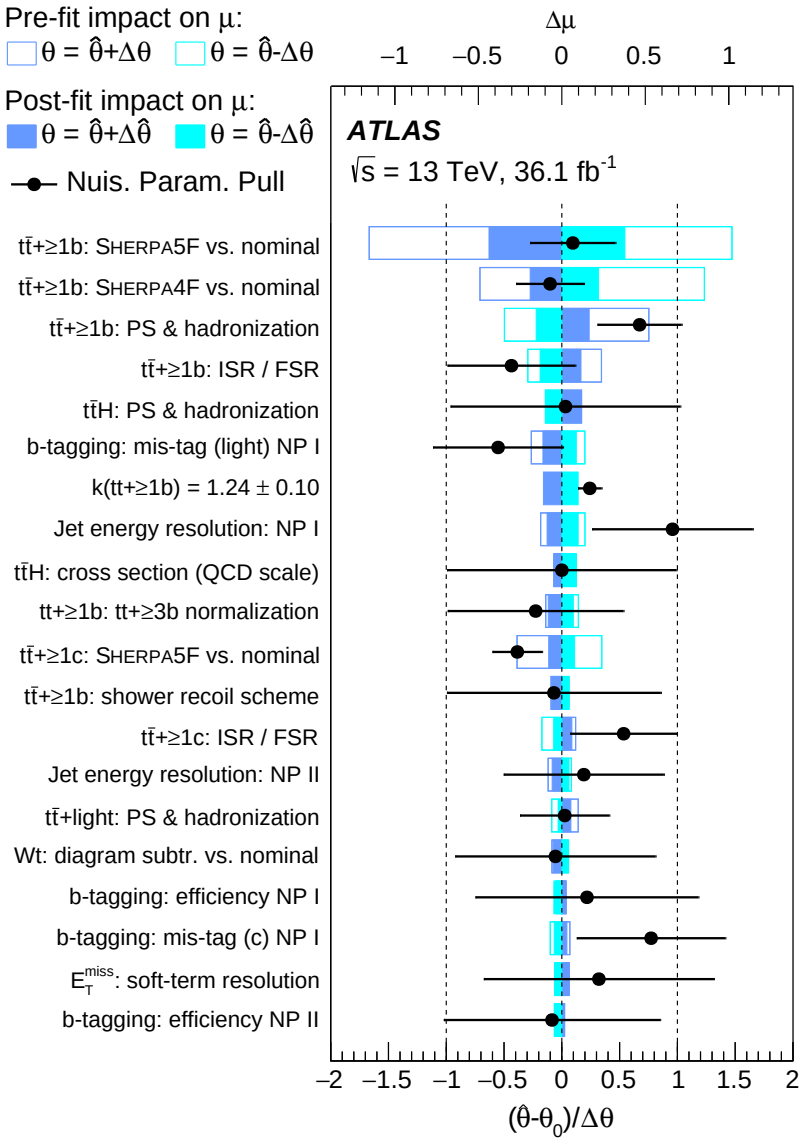
1ℓ and 2ℓ channels

ATLAS

Systematic source	Description	$t\bar{t}$ categories
$t\bar{t}$ cross-section	Up or down by 6%	All, correlated
$k(t\bar{t}+\geq 1c)$	Free-floating $t\bar{t}+\geq 1c$ normalization	$t\bar{t}+\geq 1c$
$k(t\bar{t}+\geq 1b)$	Free-floating $t\bar{t}+\geq 1b$ normalization	$t\bar{t}+\geq 1b$
Sherpa5F vs. nominal	Related to the choice of NLO event generator	All, uncorrelated
PS & hadronization	Powheg+Herwig 7 vs. Powheg+Pythia 8	All, uncorrelated
ISR / FSR	Variations of μ_{R}, μ_{F}, h_{damp} and A14 Var3c parameters	All, uncorrelated
$t\bar{t}+\geq 1c$ ME vs. inclusive	MG5_aMC@NLO+Herwig++: ME prediction (3F) vs. incl. (5F)	$t\bar{t}+\geq 1c$
$t\bar{t}+\geq 1b$ Sherpa4F vs. nominal	Comparison of $t\bar{t}+b\bar{b}$ NLO (4F) vs. Powheg+Pythia 8 (5F)	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ renorm. scale	Up or down by a factor of two	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ resumm. scale	Vary μ_{Q} from $H_{\mathrm{T}}/2$ to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ global scales	Set μ_{Q}, μ_{R}, and μ_{F} to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ shower recoil scheme	Alternative model scheme	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ PDF (MSTW)	MSTW vs. CT10	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ PDF (NNPDF)	NNPDF vs. CT10	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ UE	Alternative set of tuned parameters for the underlying event	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 3b$ normalization	Up or down by 50%	$t\bar{t}+\geq 1b$

$t\bar{t}H(\to b\bar{b})$: post-fit unc. on $\mu_{t\bar{t}H}$ [ATLAS]

1ℓ and 2ℓ channels



$t\bar{t}H(\to b\bar{b})$: $t\bar{t}+\mathrm{hf}$ modeling [CMS]

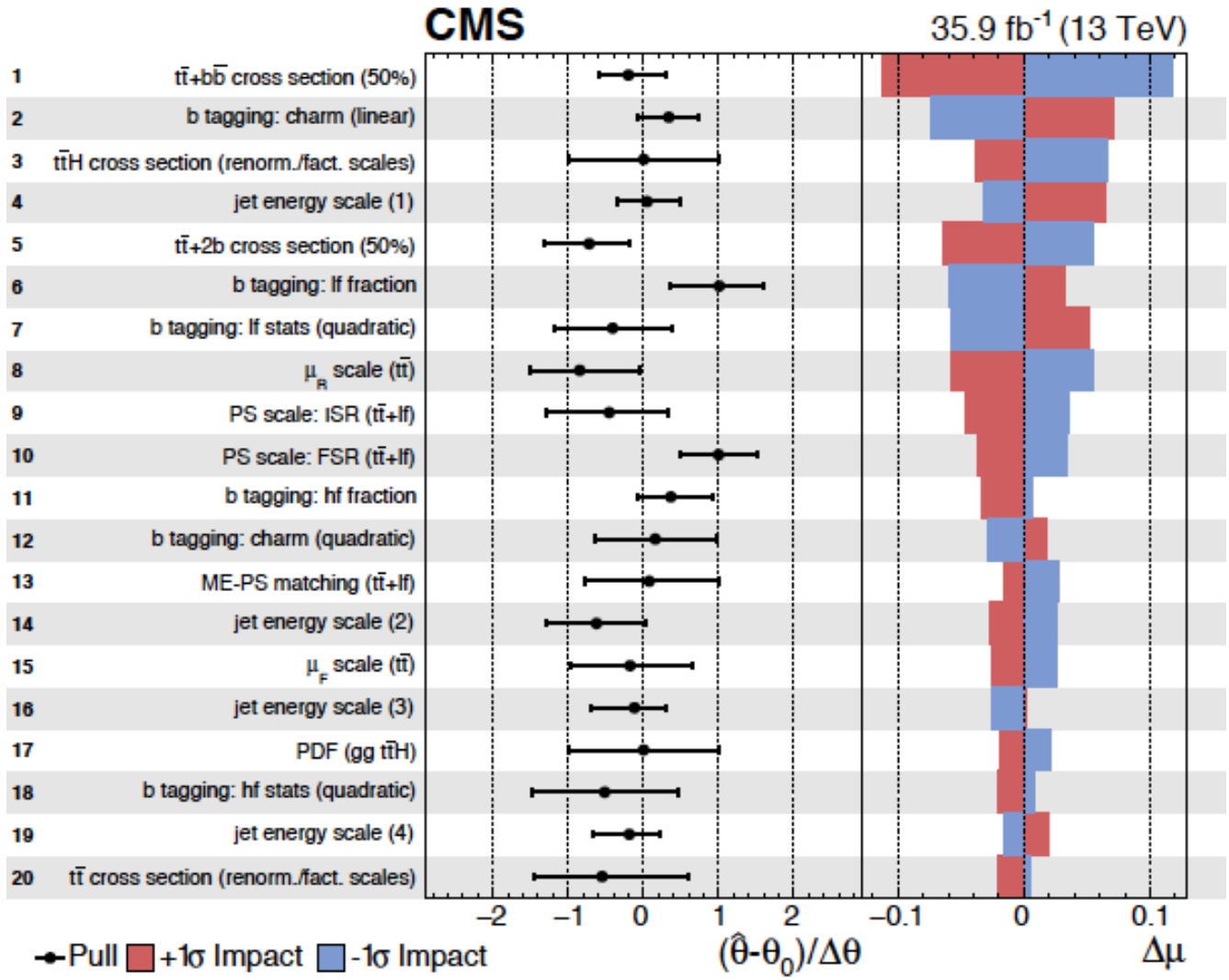
1ℓ and 2ℓ channels

CMS

Renorm./fact. scales (ttH)	rate	Scale uncertainty of NLO ttH prediction
Renorm./fact. scales ($t\bar{t}$)	rate	Scale uncertainty of NNLO $t\bar{t}$ 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 (POWHEG), same for additional jet flavours
μ_F scale ($t\bar{t}$)	shape	Factorisation scale uncertainty of the $t\bar{t}$ ME generator (POWHEG), same 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

$t\bar{t}H(\to b\bar{b})$: post-fit unc. on $\mu_{t\bar{t}H}$ [CMS]

1ℓ and 2ℓ channels



Combination of $t\bar{t}H$ searches [CMS]

HIG-17-035

uncertainties on $\mu_{t\bar{t}H}$

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

best-fit $\mu_{t\bar{t}H}$

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

tH multilepton : event yields [CMS]

HIG-18-009

Process	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}$	$\ell\ell\ell$
$t\bar{t}W$	68 ± 10	97 ± 13	22.5 ± 3.1
$t\bar{t}Z/t\bar{t}\gamma$	25.9 ± 3.9	64.8 ± 9.0	32.8 ± 5.1
WZ	15.1 ± 7.7	26 ± 13	8.2 ± 2.4
ZZ	1.16 ± 0.65	2.9 ± 1.5	1.62 ± 0.87
$W^{\pm}W^{\pm}qq$	4.0 ± 2.1	7.0 ± 3.6	—
$W^{\pm}W^{\pm}$ (DPS)	2.5 ± 1.3	4.2 ± 2.2	—
VVV	3.0 ± 1.5	4.9 ± 2.5	0.42 ± 0.26
$t\bar{t}t\bar{t}$	2.3 ± 1.2	4.1 ± 2.1	1.8 ± 1.0
tZq	5.8 ± 3.6	10.7 ± 6.1	3.9 ± 2.5
tZW	2.1 ± 1.1	3.9 ± 2.0	1.70 ± 0.86
γ conversions	—	23.8 ± 7.8	7.4 ± 2.8
Nonprompt	80.9 ± 9.4	135 ± 35	26 ± 14
Charge misidentification	—	58 ± 17	—
Total background	211 ± 17	443 ± 45	106 ± 16
$t\bar{t}H$	24.2 ± 2.1	35.2 ± 2.9	18.3 ± 1.7
tHq (SM)	1.43 ± 0.12	1.92 ± 0.15	0.52 ± 0.04
tHW (SM)	0.71 ± 0.06	1.11 ± 0.09	0.62 ± 0.05
Total SM	237 ± 17	482 ± 45	126 ± 16
tHq ($\kappa_V = 1 = -\kappa_t$)	18.5 ± 1.6	27.4 ± 2.1	7.48 ± 0.58
tHW ($\kappa_V = 1 = -\kappa_t$)	7.72 ± 0.65	11.23 ± 0.91	7.38 ± 0.60
Data	280	525	127

tH with $H \to b\bar{b}$: $t\bar{t}$ + hf def, BDT inputs [CMS]

HIG-18-009

$t\bar{t}$+b$\bar{b}$	Two additional jets arising from b hadrons
$t\bar{t}$+2b	One additional jet arising from two merged b hadrons
$t\bar{t}$+b	One additional jet arising from one b hadron
$t\bar{t}$+c$\bar{c}$	The three former categories combined for c hadrons instead of b hadrons
$t\bar{t}$+LF	All events that do not meet the criteria of the other four categories

Variable	Description
Event variables	
$\ln m_3$	Invariant mass of three hardest jets in the event
Aplanarity	Aplanarity of the event [**?**]
Fox–Wolfram #1	First Fox–Wolfram moment [**?**] of the event
$q(\ell)$	Electric charge of the lepton
$t\bar{t}$ jet assignment variables	
$\ln m(\mathrm{t_{had}})$	Invariant mass of the reconstructed hadronically decaying top quark
CSV($\mathrm{W_{had}}$ jet 1)	Output of the b tagging discriminant for the first jet assigned to the hadronically decaying W boson
CSV($\mathrm{W_{had}}$ jet 2)	Output of the b tagging discriminant for the second jet assigned to the hadronically decaying W boson
ΔR($\mathrm{W_{had}}$ jets)	ΔR between the two light jets assigned to the hadronically decaying W boson
tHq jet assignment variables	
$\ln p_{\mathrm{T}}$(H)	Transverse momentum of the reconstructed Higgs boson candidate
$\lvert\eta$(light-flavor jet)$\rvert$	Absolute pseudorapidity of light-flavor forward jet
$\ln m$(H)	Invariant mass of the reconstructed Higgs boson candidate
CSV(H jet 1)	Output of the b tagging discriminant for the first jet assigned to the Higgs boson candidate
CSV(H jet 2)	Output of the b tagging discriminant for the second jet assigned to the Higgs boson candidate
$\cos\theta(\mathrm{b_t}, \ell)$	Cosine of the angle between the b-tagged jet from the top quark decay and the lepton
$\cos\theta^*$	Cosine of the angle between the light-flavor forward jet and the lepton in the top quark rest frame
$\lvert\eta$(t) - η(H)$\rvert$	Absolute pseudorapidity difference of reconstructed Higgs boson and top quark
$\ln p_{\mathrm{T}}$(light jet)	Transverse momentum of the light-flavor forward jet
tHW jet assignment variable	
JA-BDT response	Best output of the tHW JA-BDT

tH combination : post-fit uncertainties [CMS]

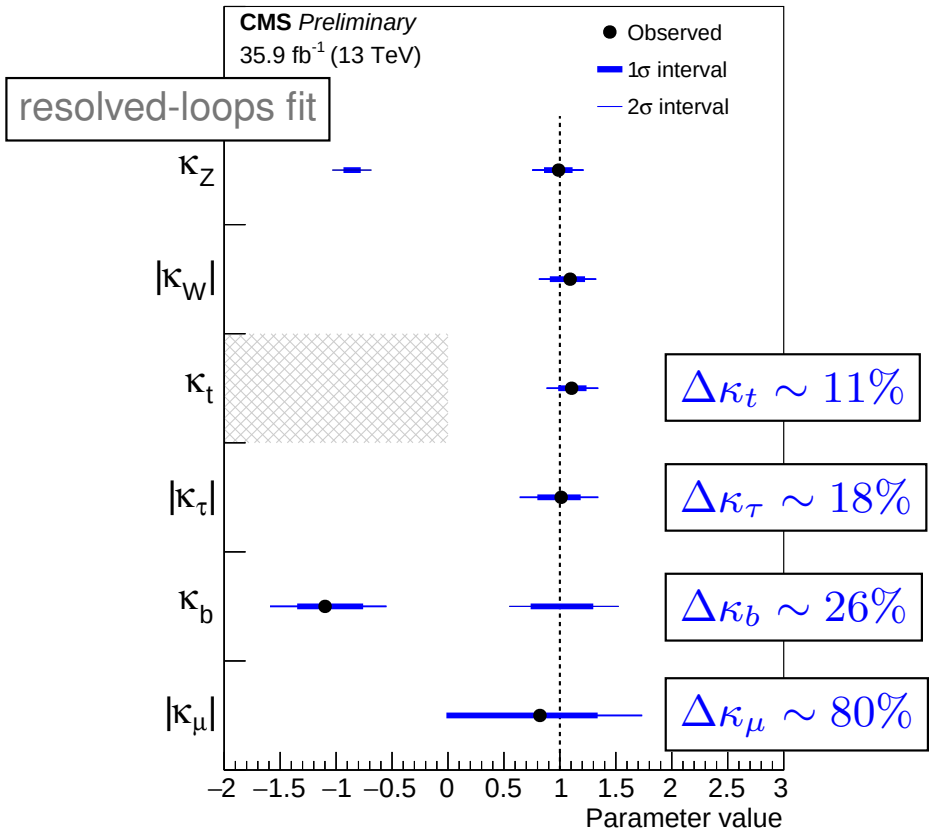
HIG-18-009

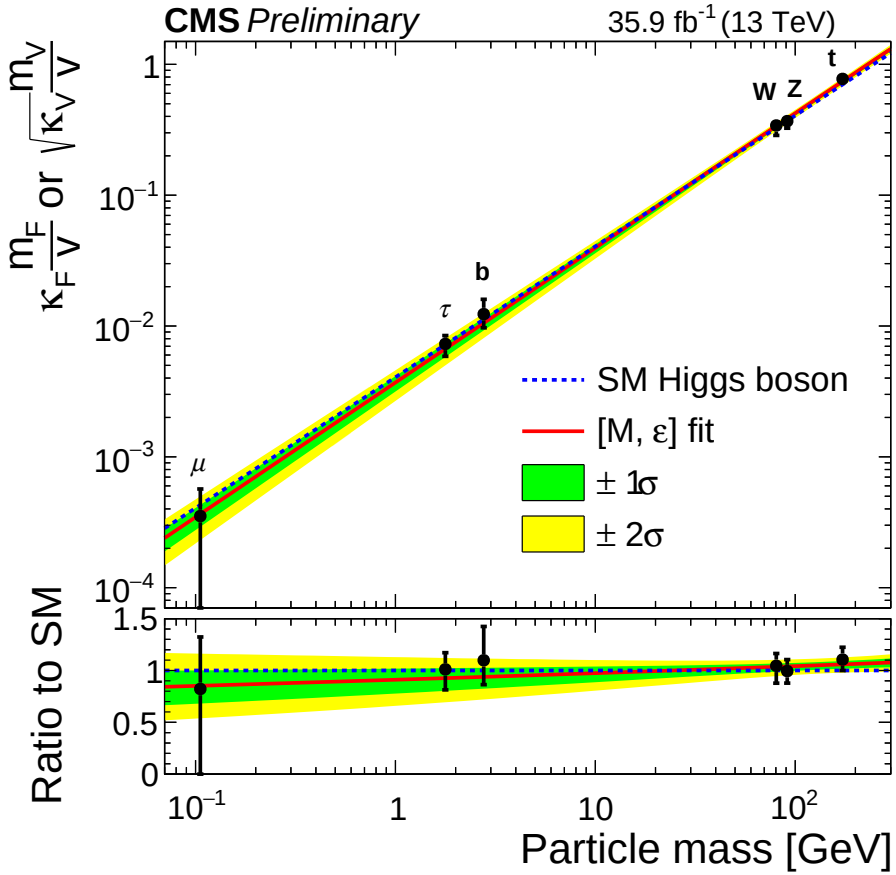
Source	Uncertainty [%]	$\Delta\mu/\mu$ [%]
e, μ selection efficiency	2–4	17
b tagging efficiency	2–15	6
Jet energy calibration	2–15	3
Forward jet modeling	10–35	3
Integrated luminosity	2.5	10
Reducible background estimate	10–40	14
Theoretical sources	≈10	14
$t\bar{t}$+HF normalization	≈50	7
PDFs	2–6	8

Yukawa couplings in combined Higgs analyses

HIG-17-031

- combined measurements of Higgs boson couplings with 2016 data
- showing only fit assuming SM expr. for ggF and $H(\gamma\gamma)$ loops





HL-LHC Projections

Higgs Physics at the HL-LHC and HE-LHC

- ATLAS and CMS projections for physics analyses at HL-LHC
- $\Delta\sigma_{t\bar{t}H} = 4.3\%$ (S2) projected for ATLAS+CMS at $3000\ \mathrm{fb}^{-1}$ per experim.
  - S2: assumes lumi-scaling of some syst, and reduced theory unc.