Latest CMS results on $t\bar{t}H$ production in the $H \to b\bar{b}$ channel

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LHC Physics Discussion

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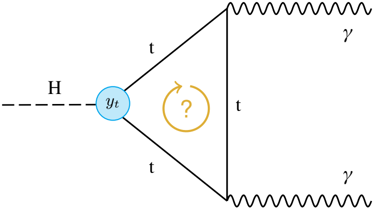
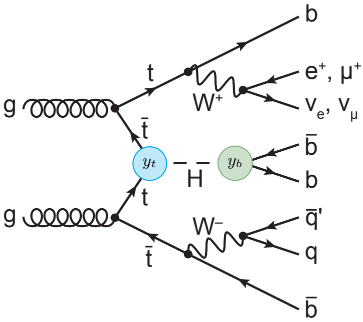
Higgs coupling to fermions

- key test of the properties of $H(125)$
  - in the SM: Yukawa couplings ($\propto m_f$)

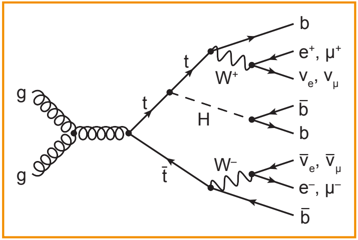
- Top quark:
  strongest coupling to SM Higgs ($y_t \simeq 1$)
  - indirect, model-dependent, constraints on top-Higgs coupling from ggH and $H \to \gamma\gamma$
  - direct measurement with best sensitivity to $|y_t|$ at LHC: $t\bar{t}H$ production cross section

- *this talk* : $t\bar{t}H(\to b\bar{b})$ channel
  - $H \to b\bar{b}$: largest SM Higgs BR (58%)
  - sensitive to both $|y_t|$ and $|y_b|$





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



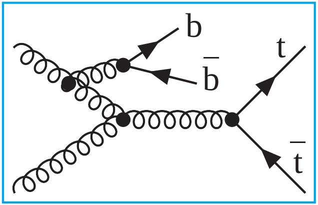
- final states with up to 4 b-jets:

Fully-Hadronic (FH) :	0ℓ + $\geqslant 7$ jets
Single-Lepton (SL) :	1ℓ + MET + $\geqslant 4$ jets
Dilepton (DL) :	$\ell^{\pm}\ell'^{\mp}$ (+ MET) + $\geqslant 3$ jets

- backgrounds:
  - $t\bar{t}+$ jets , w/ irreducible $t\bar{t}+b\bar{b}$: modeled with MC, applying additional uncs to $t\bar{t}$+heavy-flavor (hf) processes
  - [FH] large QCD multijet bkg (data-driven)

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

- b-tagging crucial, to separate tt+bb from tt+jj

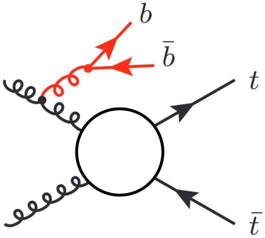


- no easy variable to separate ttH(bb) from tt+bb:
  - large (b-)jets combinatorics hinders $H(b\bar{b})$ reco
  - final discriminants based on MVA methods

$t\bar{t}+b\bar{b}$: modeling and measurements

FS: Flavor Scheme
5FS: massless b quarks, included in PDF
4FS: massive b quarks, only from $g \to b\bar{b}$

- $t\bar{t}+b\bar{b}$: complex multi-scale process
- different types of MC simulations being studied and compared (see, for example, $t\bar{t}+b\bar{b}$ studies in LHCHXSWG)
  - $t\bar{t}$ ME at NLO, + PS $g \to b\bar{b}$ (5FS)
  - $t\bar{t}+0/1/2$ jets ME at NLO (5FS)
  - $t\bar{t}+b\bar{b}$ ME at NLO (4FS)



- $t\bar{t}+b\bar{b}$ measurements at the LHC:
  - unc. on incl. cross section ∼20%, dominated by systematics
  - measured cross section 30-50% larger than MC predictions
  - differential distr: different predictions describe Data within uncertainties

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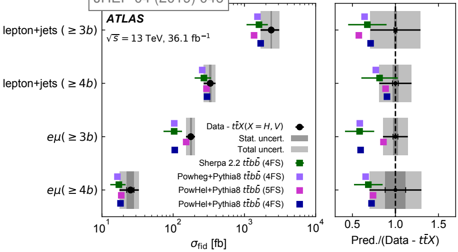
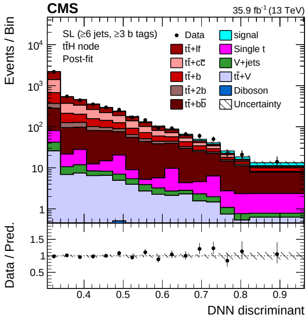


Reminder: $t\bar{t}H(\to b\bar{b})$ results with 2016 CMS Data

Integrated Luminosity: $35.9\ \mathrm{fb}^{-1}$

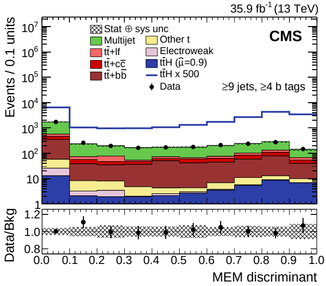
HIG-17-026: Single-Lepton and Dilepton

- $\mu_{\mathrm{fit}} = 0.72 \pm 0.24\ (\mathrm{stat}) \pm 0.38\ (\mathrm{syst})$
- Obs (Exp) Significance: $1.6\sigma\ (2.2\sigma)$



HIG-17-022: Fully-Hadronic

- $\mu_{\mathrm{fit}} = 0.9 \pm 0.7\ (\mathrm{stat}) \pm 1.3\ (\mathrm{syst})$
- Obs (Exp) 95% CL limit: $\mu < 3.8\ (3.1)$



inputs to CMS combinations that led to $t\bar{t}H$ and $H \to b\bar{b}$ observations in 2018

Latest CMS results on $t\bar{t}H(\rightarrow b\bar{b})$

CMS-PAS-HIG-18-030 (March 2019) :

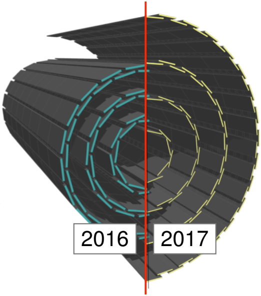
$t\bar{t}H(\rightarrow b\bar{b})$ with 2017 Data (+ combination with existing 2016 results)

- analysis strategy similar to 2016
- improvements for 2017 analysis:
  - larger dataset ($41.5\ \mathrm{fb}^{-1}$ in 2017 + combination with existing 2016 results)
  - combination of 3 $t\bar{t}H(b\bar{b})$ channels (FH, SL, DL)
  - improved detector (CMS Phase-1 Pixel)
  - improved jet b-tagging (CSVv2 $\rightarrow$ DeepCSV)
  - modeling of $t\bar{t}$ uncertainties (ISR/FSR from Parton-Shower weights)

Phase-1 Pixel upgrade and improved b-tagging

CMS Phase-1 Pixel upgrade (2017)

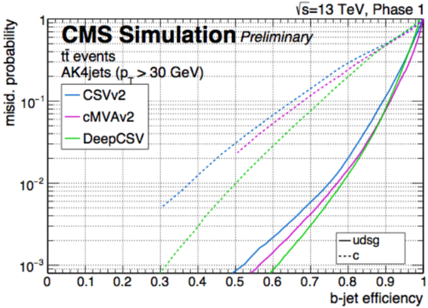
- 4 layers (barrel Pi) + 3 disks (forward Pi)
- new readout, reduced material budget
- improved tracking efficiency, vtx resolution



b-tagger: CSVv2 → DeepCSV

- DeepCSV: evolution of CSVv2 to a feed-forward DNN arch. with similar inputs

CMS-DP-2017-005 CMS-DP-2017-013



- per-jet tagging efficiency for true b-jets (1% mistag rate):

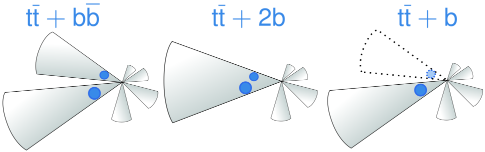
[Phase-0 Pixel + CSVv2] 65% → 78% [Phase-1 Pixel + DeepCSV]

Modeling of $t\bar{t}$ bkg

- $t\bar{t}$ MC: POWHEG + PYTHIA8 ($t\bar{t}$ ME at NLO, 5FS)
    - normalised to NNLO+NNLL inclusive $t\bar{t}$ cross-section: 832 pb
    - additional b-jets (not from t decay) modeled by Parton Shower

- $t\bar{t}$ events split into 5 $t\bar{t} + xy$ sub-processes based on flavor content of GEN-jets not associated to $t\bar{t}$ decay: $t\bar{t} + b\bar{b}$, $t\bar{t} + 2b$, $t\bar{t} + b$, $t\bar{t} + c\bar{c}$ and $t\bar{t} + \mathrm{lf}$

- treated as 5 separate processes with (mostly) independent systematics:
    - large prior unc. (50%) on norm. of $t\bar{t} + b\bar{b}$, $t\bar{t} + 2b$, $t\bar{t} + b$ and $t\bar{t} + c\bar{c}$
    - μ_R, μ_F, PDF, ISR and FSR: shape+rate variations from MC weights
    - unc. on ME-PS matching (`hdamp`) and UE-Tune from dedicated MC samples

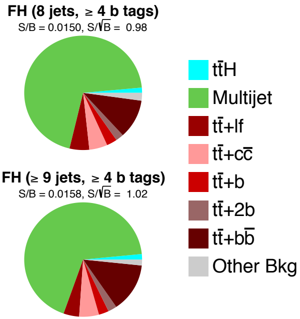


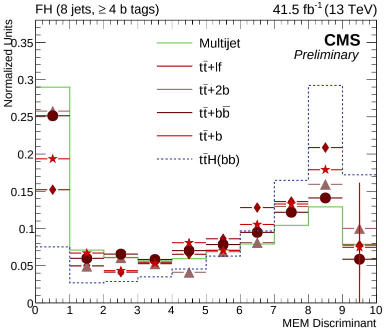
$t\bar{t} + b\bar{b}$, $t\bar{t} + 2b$ and $t\bar{t} + b$ contribute in different measures to the various $t\bar{t}H(b\bar{b})$ SRs

- bkg model with flexibility to account for differences wrt Data, and other predictions

Fully-Hadronic channel

- total of 6 SRs based on # of jets (7j, 8j, $\geqslant 9$j) and b-tags (3b, $\geqslant 4$b)
- largest bkg: QCD multijet (data-driven)
  - $\sim 70\%$ of tot-bkg in $\geqslant$4b SRs
  - other bkgs ($t\bar{t}+$jets) from MC
- final discriminant in each SR: Matrix Element Method (MEM)
  - based on $t\bar{t}H$ and $t\bar{t}+b\bar{b}$ LO MEs
  - quantifies compatibility of reconstructed final state with signal ($t\bar{t}H$) and bkg ($t\bar{t}+b\bar{b}$) hypotheses

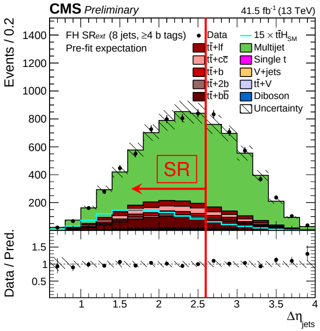


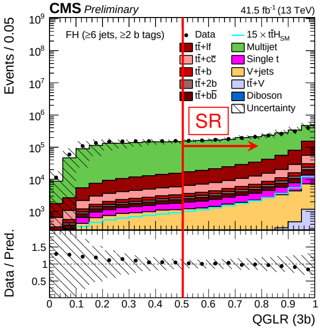


Fully-Hadronic channel

Handles to reduce QCD multijet background

1. a W-like dijet pair
   - ttH events contain W bosons
     $\rightarrow$ require dijet with m_{jj} in W mass window
2. jet angular distances
   - QCD multijet: max. $\Delta\eta$ between 2 jets
     on average larger than for ttH events
3. quark-jets vs gluon-jets
   - $t\bar{t}H(b\bar{b})$: quark-initiated jets
   - QCD: dominated by gluon-initiated jets
   - quark/gluon discriminant: probability
     of jet to originate from quark parton
   - cut on Quark Gluon Likel. Ratio (QGLR):
     4-quark-jets vs 4-gluon-jets hypotheses

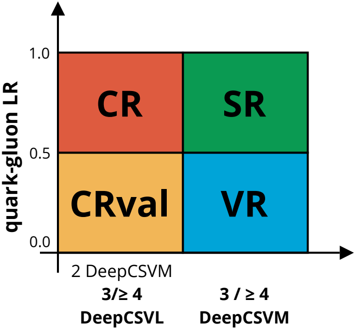


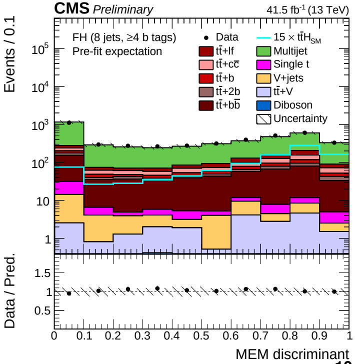


Fully-Hadronic channel

Data-driven QCD bkg and SR discriminants

- QCD multijet bkg in SRs:
  - determined from Data using CRs defined by $N_{\text{b-tags}}$ and QGLR [more details in BACKUP]
  - data-driven estimate done separately for each of the 6 SRs
  - normaliz. of QCD multijet bkg freely-floating in S+B fit (6 parameters, 1 per categ)
- Final discriminants (MEM) in FH SRs:
  - most sensitive SRs in FH channel: 8j, $\geqslant$4b and $\geqslant$9j, $\geqslant$4b
  - expected significance for SM $t\bar{t}H$: 0.7σ





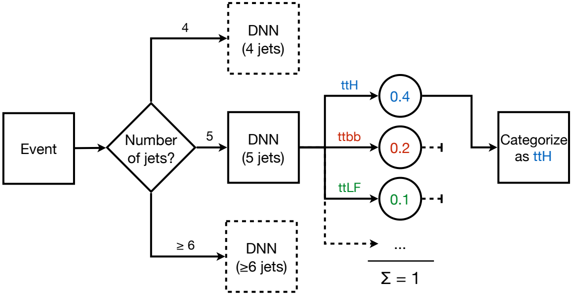
Single-Lepton channel

- 3 SL samples based on jet multiplicity (4j, 5j, $\geqslant$6j), each with $\geqslant$3 b-tags
  - over 90% of bkg from $t\bar{t}$ + jets (modeled with MC)

- each sample further split into 6 SRs
  based on multi-class Neural Network with 6 output nodes:

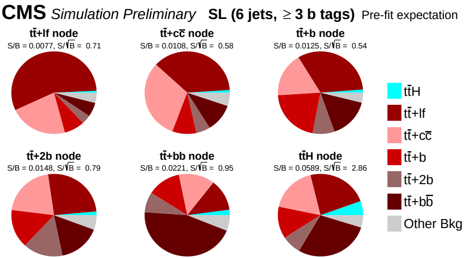
$t\bar{t}H$ node	$t\bar{t}+b\bar{b}$ node	$t\bar{t}+2b$ node	$t\bar{t}+b$ node	$t\bar{t}+c\bar{c}$ node	$t\bar{t}+\mathrm{lf}$ node

- event classified based on highest value of NN outputs
- leads to categs enriched in signal (ttH) or a given $t\bar{t}$ proc.
- results in total of 18 SRs



Single-Lepton channel

Signal Regions, NN training and validation

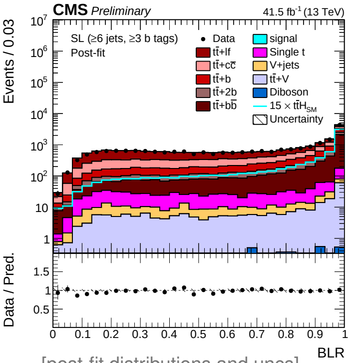


$t\bar{t} + b\bar{b}$ nodes : $t\bar{t} + b\bar{b}$ up to 45% of bkg

$t\bar{t}H$ nodes : S/B up to 6%

- For every SR, NN output used as final discriminant in S+B fit

- NN architecture and validation:
  - feed-forward network with 3 hidden layers
  - inputs: MEM, b-tagging, obj kinematics (e.g. angular distances, inv. masses)
  - modeling of inputs and their correlations validated in Data with 1D and 2D goodness-of-fit tests incl. all syst uncs

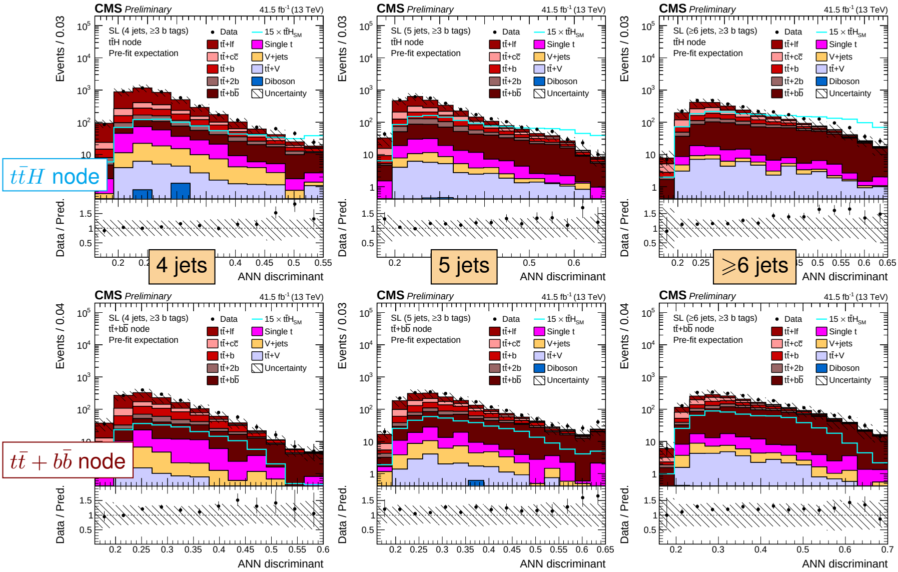


[post-fit distributions and uncs]

Single-Lepton channel

expected significance: 1.9σ

Final discriminants ($t\bar{t}H$ and $t\bar{t}+b\bar{b}$ nodes): pre-fit

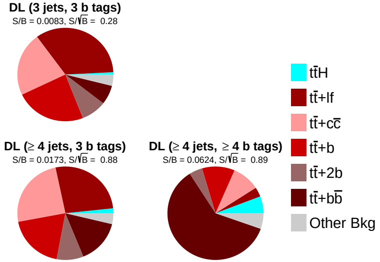


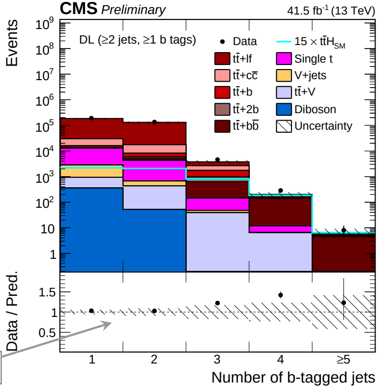
Dilepton channel

- 5 SRs based on # of jets and b-tags:

3j, 2b	3j, 3b	⩾4j, 2b	⩾4j, 3b	⩾4j, ⩾4b

- $t\bar{t}$ bkg: $\geqslant 95\%$ of total bkg
- most sensitive SRs: 4j3b and 4j4b
  - 4j4b SR: $t\bar{t}+b\bar{b} \sim 64\%$ of bkg, $S/B \sim 6\%$
- DL events with $\geqslant 4$ b-tags: purest sample of $t\bar{t}+b\bar{b}$ events
- Data/MC discrepancy at high $N_{\text{b-tags}}$: imperfect prediction of $t\bar{t}+b\bar{b}$ xsec



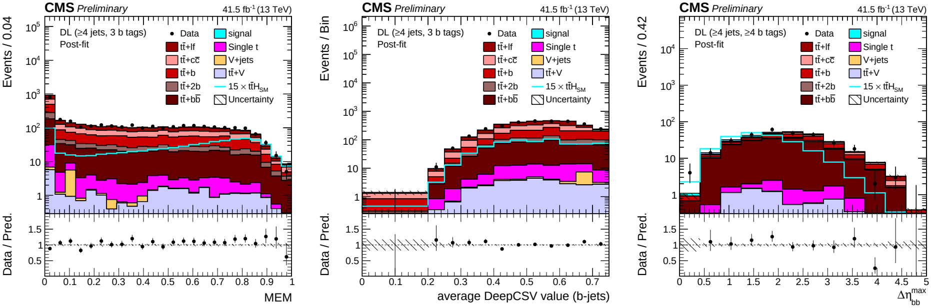


error band: all syst (except 50% unc on $t\bar{t}+\text{hf}$ norm)

Dilepton channel

BDT training and inputs

- final discriminants: binary BDT trained for $t\bar{t}H(\rightarrow b\bar{b})$ vs $t\bar{t}$
  - BDT optimized independently in each categ (algorithm: gradient boosting)
  - inputs: MEM, b-tagging, obj kinematics (e.g. angular distances, inv. masses) modeling of each input validated with Data (similar to SL)

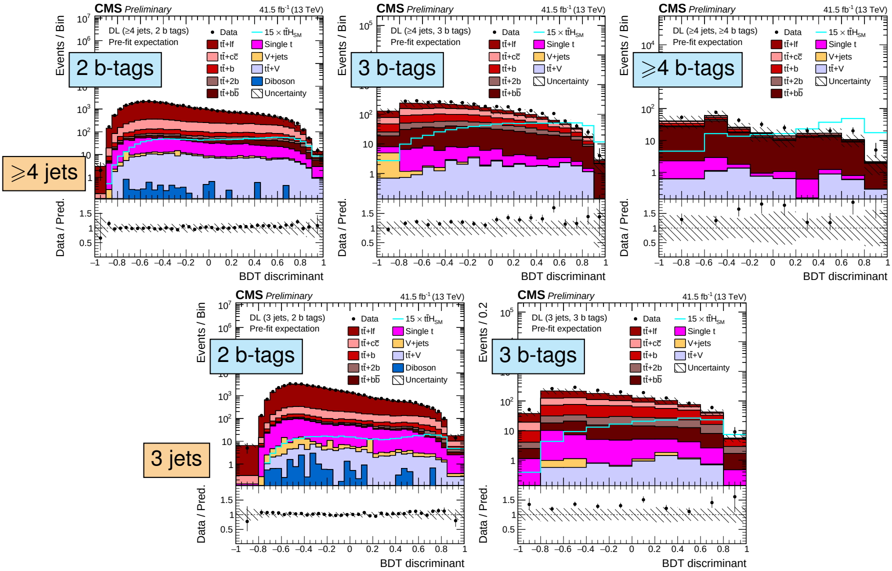


[post-fit distributions and uncs]

Dilepton channel

expected significance: 1.2σ

Final discriminants: pre-fit



Systematic uncertainties

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
Trigger prefiring correction	rate	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
QGL reweighting	shape	Signal and all backgrounds
TF_{loose} correction	shape	QCD multijet estimate
H_T reweighting	shape	QCD multijet estimate
Multijet normalisation	rate	QCD multijet estimate
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 NNLO $t\bar{t}$ prediction
$t\bar{t}$+hf cross sections	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)
PDF shape variations ($t\bar{t}H$, $t\bar{t}$)	shape	Based on the NNPDF replicas, same for $t\bar{t}H$ and additional jet flavours
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 ($t\bar{t}$)	shape	Initial state radiation uncertainty of the PS (for $t\bar{t}$ events), same for additional jet flavours
PS scale: FSR ($t\bar{t}$)	shape	Final state radiation uncertainty of the PS (for $t\bar{t}$ events), same for additional jet flavours
ME-PS matching ($t\bar{t}$)	rate	NLO ME to PS matching, *hdamp* [?] (for $t\bar{t}$ events), independent for additional jet flavours
Underlying event ($t\bar{t}$)	rate	Underlying event (for $t\bar{t}$ events), independent for additional jet flavours
Bin-by-bin event count	shape	Statistical uncertainty of the signal and background prediction due to the limited sample size

Experimental uncertainties:

- 20 (8) separate sources for jet energy scale/resolution (jet b-tagging) corrections

FH-specific systematics:

- uncs on data-driven QCD bkg estimate
- norm. of QCD bkg (1 free param. per categ)

50% tt+hf xsec uncertainty (one per tt+hf proc.):

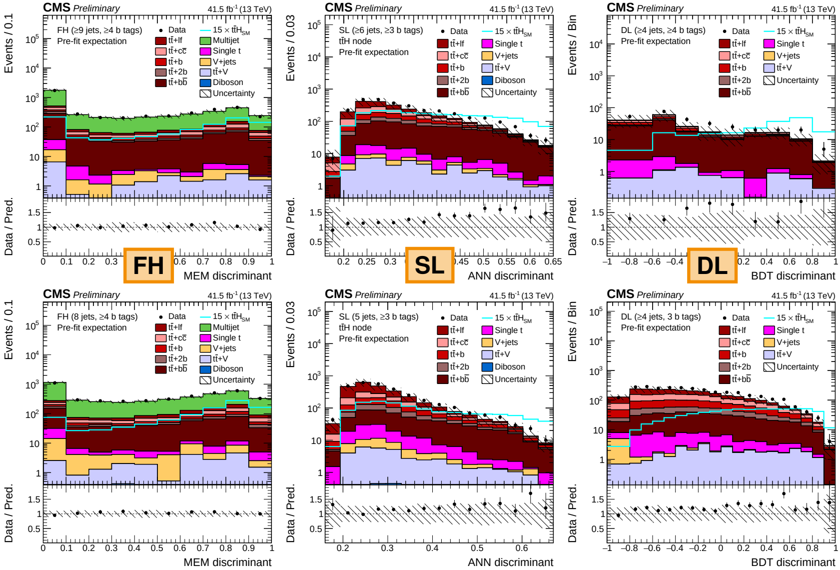
- larger priors, or freely-floating params, also tested

ISR/FSR, `hdamp` and UE (only for $t\bar{t}$ MC):

- separate nuisances for different tt+hf proc.
- ISR/FSR: shape uncertainty (PS weights)
- `hdamp` and UE: rate-only unc. (limited MC stats) with different prior for each proc. and categ.

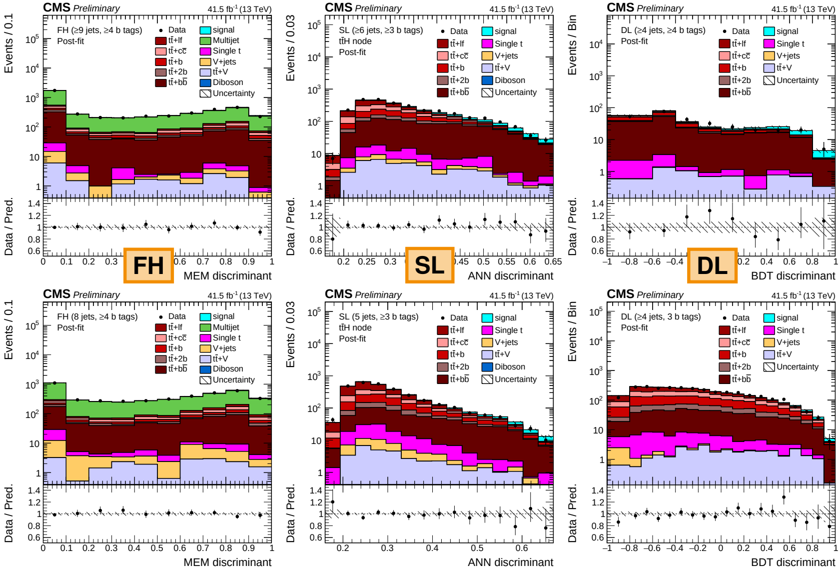
Final Discriminants : pre-fit

2 most sensitive categories of each 2017 channel



Final Discriminants : post-fit [2017 fit]

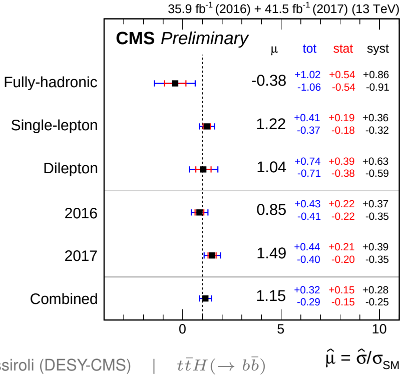
2 most sensitive categories of each 2017 channel

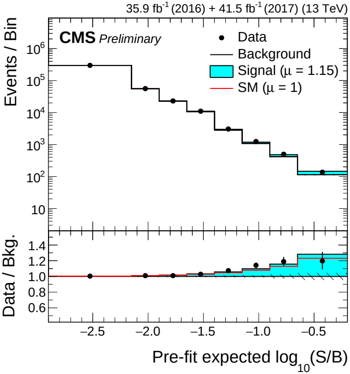


2017 and 2016+2017 Fit Results

$t\bar{t}H$ signal strength and significance

	Best-fit $\hat{\mu}_{\text{obs}}$	Obs. (Exp.) Significance
2016 SL+DL	0.72 ± 0.24 (stat) ± 0.38 (syst)	1.6σ (2.2σ)
2017 FH+SL+DL	$1.49\,^{+0.21}_{-0.20}$ (stat) $^{+0.39}_{-0.35}$ (syst)	3.7σ (2.6σ)
2016+2017 FH+SL+DL	$1.15\,^{+0.15}_{-0.15}$ (stat) $^{+0.28}_{-0.25}$ (syst)	3.9σ (3.5σ)





Impact of systematics on $\Delta\mu_{t\bar{t}H}$ [2016+2017 fit]

- systematics with largest impact on $\Delta\mu_{t\bar{t}H}$:
  - unc. on $t\bar{t}H$ cross section
  - tt+hf modeling
    [cross section, ISR/FSR,
    ME-PS matching, MC Tune, ME scale]
  - QCD modeling in FH channel
  - jet energy corrections, b-tagging eff.
  - statistics of MC samples

Uncertainty source	$\Delta\hat{\mu}$
Total experimental	$+0.15/-0.13$
b tagging	$+0.08/-0.07$
jet energy scale and resolution	$+0.05/-0.04$
Total theory	$+0.23/-0.19$
signal	$+0.15/-0.06$
$t\bar{t}$+hf modelling	$+0.14/-0.15$
QCD background prediction	$+0.10/-0.08$
Size of simulated samples	$+0.10/-0.10$
Total systematic	$+0.28/-0.25$
Statistical	$+0.15/-0.15$
Total	$+0.32/-0.29$

Summary

- presented latest CMS result on $t\bar{t}H(b\bar{b})$, based on 2017 Data $(41.5\ \mathrm{fb}^{-1})$
- once combined with 2016 analysis, the measured signal strength corresponds to

$$\hat{\mu}_{\text{obs}} = 1.15^{+0.32}_{-0.29} = 1.15\,^{+0.15}_{-0.15}\ \text{(stat)}\ ^{+0.28}_{-0.25}\ \text{(syst)}$$

  for an observed significance of 3.9σ (expected: 3.5σ)
- compatible with SM prediction
- a stepping stone towards legacy Run-2 result on $t\bar{t}H(b\bar{b})$:
  - combination of SL/DL and FH channels
  - understanding of 2017 Data
  - introduction of new b-tagger
  - refinement of analysis methods (e.g. ISR/FSR syst)
- strong and continued contribution of DESY-CMS group in this channel

BACKUP

$t\bar{t}H(\rightarrow b\bar{b})$ [CMS, 2017]

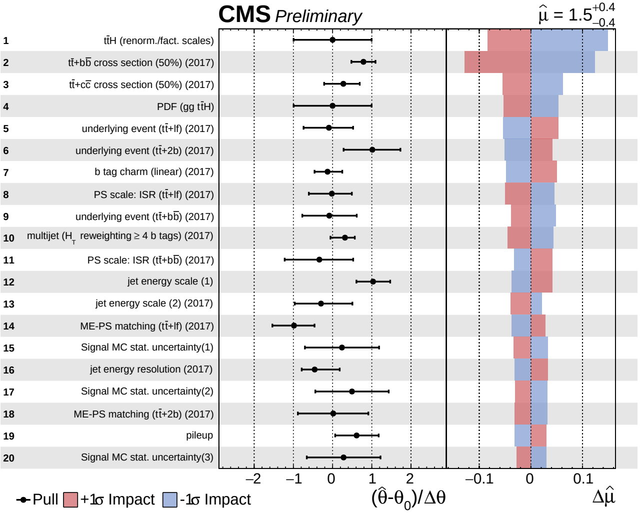
Correlation scheme for 2016/17 systematics

Uncertainty	Treatment	Comment
Experimental Unc. (lumi, trig, lept-ID, b-tag, JECs)	decorrelated	except for PU
FH Multijet background	decorrelated	CR statistics in different data sets
$t\bar{t}$ ISR/FSR	decorrelated	varied samples (2016) vs PS-weights (2017)
$t\bar{t}$ UE	decorrelated	different MC Tunes in 2016 and 2017
$t\bar{t}$ `hdamp`	decorrelated	different `hdamp` values in 2016 and 2017 MC
PDF shapes on $t\bar{t}H$ and $t\bar{t}$	decorrelated	NNPDF 3.0 (2016), NNPDF 3.1 (2017)
50% norm. unc. on tt+HF processes ($b\bar{b}$, $2b$, b, $c\bar{c}$)	decorrelated	different Tune and `hdamp` in 2016 and 2017 MC
$t\bar{t}H$ and $t\bar{t}$ x-sec unc. from PDF and scale variations	correlated	calculations from theory
μ_F/μ_R scale variations in $t\bar{t}$ MC (shape)	correlated	same implementation in 2016 and 2017 MCs

- some tt+hf modeling uncertainties kept decorrelated across years because of different MC Tunes in 2016 and 2017 MC
- tested several different choices for correlation schemes and tt+hf priors: small impact on expected results (less than 3% on $\Delta\mu_{t\bar{t}H}$)

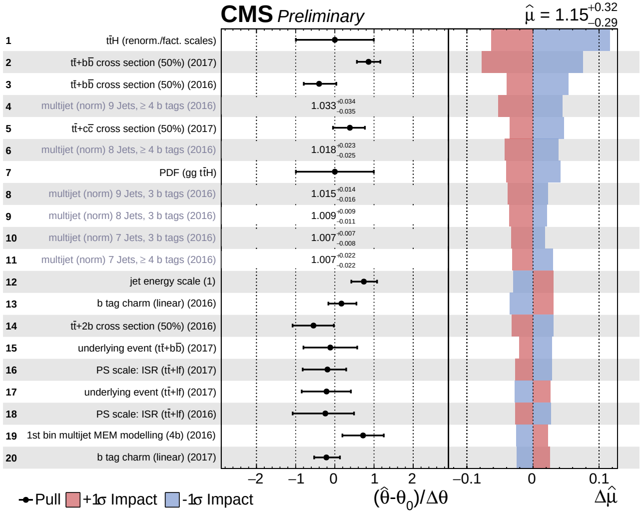
$t\bar{t}H(\to b\bar{b})$ [CMS, 2017]

Impact of systematics on $\Delta\mu_{t\bar{t}H}$ [2017 fit]



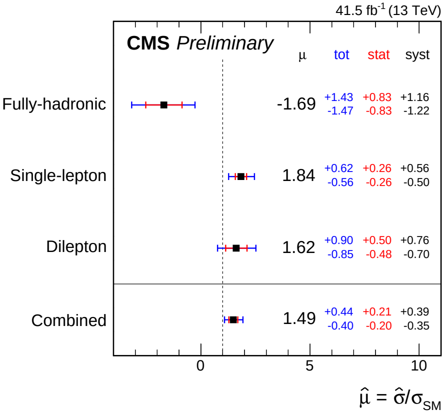
$t\bar{t}H(\to b\bar{b})$ [CMS, 2017]

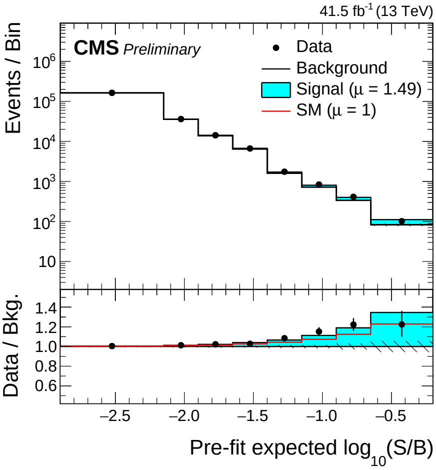
Impact of systematics on $\Delta\mu_{t\bar{t}H}$ [2016+2017 fit]



$t\bar{t}H(\rightarrow b\bar{b})$ [CMS, 2017]

2017 Fits and $\log S/B$ plot





$t\bar{t}H(\rightarrow b\bar{b})$ [CMS, 2017]

Signal strength and significance per channel

	$\hat{\mu}$ ± tot (±stat ± syst)	significance obs (exp)
FH 3 b-tags	$1.36^{+3.57}_{-5.36}$ $\left(^{+1.68}_{-1.69}\ ^{+3.15}_{-5.09}\right)$	$0.3\,\sigma$ $(0.2\,\sigma)$
FH 4 b-tags	$-1.54^{+1.41}_{-1.45}$ $\left(^{+0.91}_{-0.90}\ ^{+1.08}_{-1.13}\right)$	— $(0.7\,\sigma)$
FH combined	$-1.69^{+1.43}_{-1.47}$ $\left(^{+0.83}_{-0.83}\ ^{+1.16}_{-1.22}\right)$	— $(0.7\,\sigma)$
SL 4 jets	$1.73^{+2.25}_{-2.21}$ $\left(^{+0.88}_{-0.87}\ ^{+2.07}_{-2.04}\right)$	$0.8\,\sigma$ $(0.5\,\sigma)$
SL 5 jets	$0.73^{+0.98}_{-0.97}$ $\left(^{+0.47}_{-0.46}\ ^{+0.86}_{-0.86}\right)$	$0.8\,\sigma$ $(1.0\,\sigma)$
SL $\geq$ 6 jets	$2.05^{+0.76}_{-0.69}$ $\left(^{+0.31}_{-0.31}\ ^{+0.69}_{-0.62}\right)$	$3.0\,\sigma$ $(1.6\,\sigma)$
SL combined	$1.84^{+0.62}_{-0.56}$ $\left(^{+0.26}_{-0.26}\ ^{+0.56}_{-0.50}\right)$	$3.3\,\sigma$ $(1.9\,\sigma)$
DL 3 jets	$-2.35^{+4.40}_{-2.65}$ $\left(^{+2.13}_{-2.06}\ ^{+3.85}_{-1.66}\right)$	— $(0.2\,\sigma)$
DL $\geq$ 4 jets	$1.57^{+1.02}_{-0.98}$ $\left(^{+0.55}_{-0.53}\ ^{+0.86}_{-0.82}\right)$	$1.6\,\sigma$ $(1.0\,\sigma)$
DL combined	$1.62^{+0.90}_{-0.85}$ $\left(^{+0.50}_{-0.48}\ ^{+0.76}_{-0.70}\right)$	$1.9\,\sigma$ $(1.2\,\sigma)$
FH+SL+DL combined	$1.49^{+0.44}_{-0.40}$ $\left(^{+0.21}_{-0.20}\ ^{+0.39}_{-0.35}\right)$	$3.7\,\sigma$ $(2.6\,\sigma)$
FH+SL+DL combined 2016+2017	$1.15^{+0.32}_{-0.29}$ $\left(^{+0.15}_{-0.15}\ ^{+0.28}_{-0.25}\right)$	$3.9\,\sigma$ $(3.5\,\sigma)$

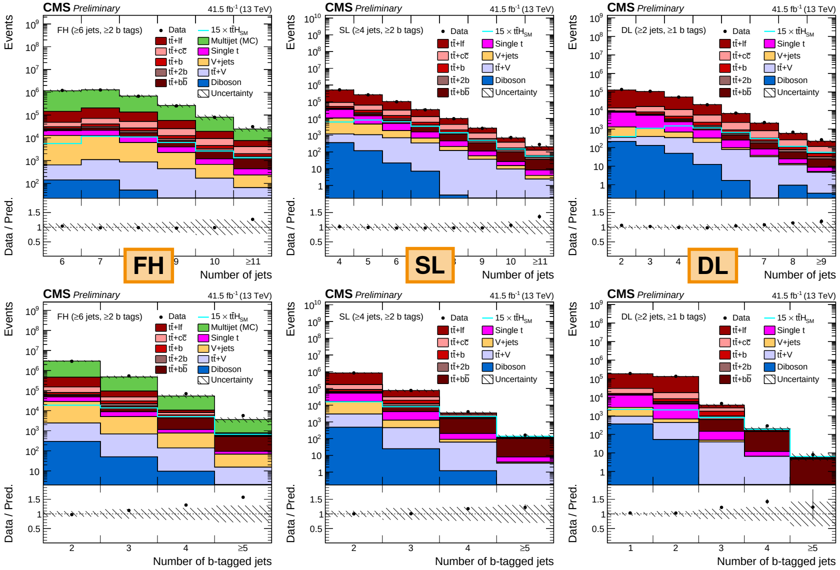
$t\bar{t}H(\rightarrow b\bar{b})$ [CMS, 2017]

Baseline event selection

	FH channel	SL channel	DL channel
Number of leptons	0	1	2
p_T of leptons (e/μ) [GeV]	—	$> 30/29$	$> 25/25$ GeV
p_T of additional leptons [GeV]	< 15	< 15	< 15
$\lvert\eta\rvert$ of leptons	< 2.4	< 2.4	< 2.4
Number of jets	≥ 6	≥ 4	≥ 2
p_T of jets [GeV]	> 40	> 30	$> 30, 30, 20$
$\lvert\eta\rvert$ of jets	< 2.4	< 2.4	< 2.4
Number of b-tagged jets	≥ 2	≥ 2	≥ 1
p_T^{miss}	—	> 20 GeV	> 40 GeV

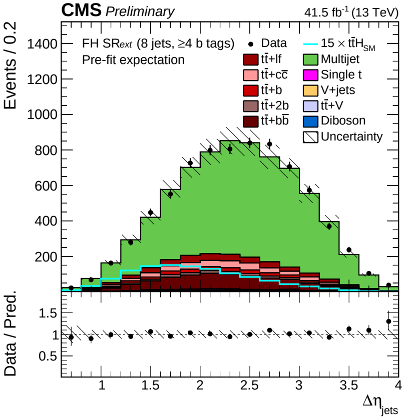
$t\bar{t}H(\to b\bar{b})$ [CMS, 2017]

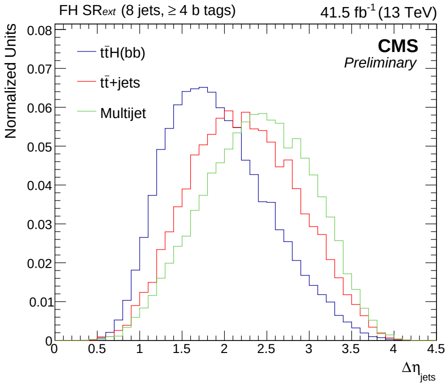
Baseline event selection: N_{jets} and $N_{\text{b-tags}}$



$t\bar{t}H(\rightarrow b\bar{b})$ [CMS, 2017]

Fully-Hadronic channel

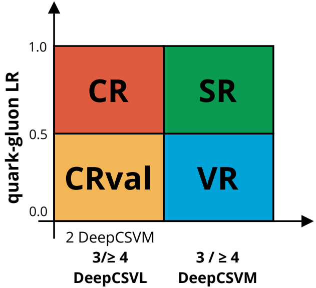




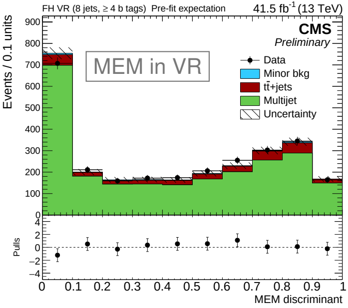
$t\bar{t}H(\rightarrow b\bar{b})$ [CMS, 2017]

Fully-Hadronic channel: Data-driven QCD multijet bkg

- **SR** : $\geqslant$3 b-tags
- **CR** : 2 b-tags ($\geqslant$3 loose b-tags)
- **VR** : (Validation Reg.) fails cut on q/g discrim.



- QCD bkg shape from Data−MC in **CR**
- correct shape for CR→SR diffs in b-tag kinematics: correction parameterized with MC as function of jet p_T, η and $\Delta R^{\text{min}}_{jb}$

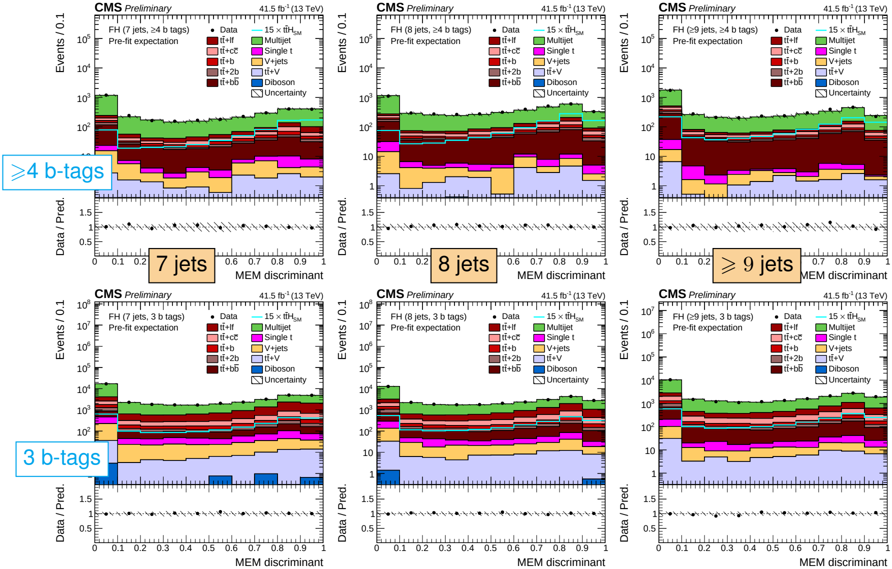


- QCD multijet norm. freely-floating in final fit (6 parameters, 1 per categ)
- **CRval** and **VR** used to validate method and assign systematics

$t\bar{t}H(\rightarrow b\bar{b})$ [CMS, 2017]

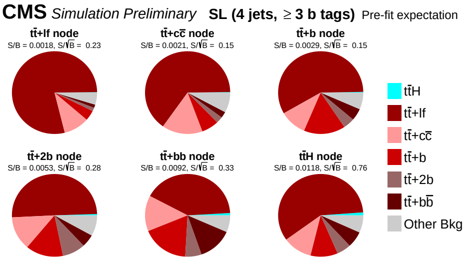
Fully-Hadronic channel: Final discriminants (pre-fit)

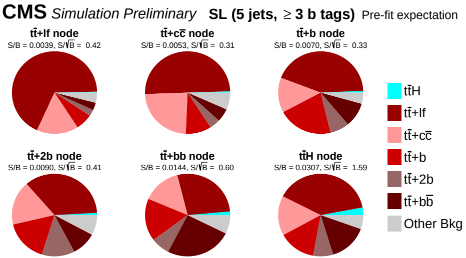
expected significance: 0.7σ



$t\bar{t}H(\to b\bar{b})$ [CMS, 2017]

Single-Lepton channel





$t\bar{t}H(\rightarrow b\bar{b})$ [CMS, 2017]

SR Event Yields [2017 fit]: Fully-Hadronic channel

Process	(7 jets, 3 b-tags)		(7 jets, $\geq$ 4 b-tags)		(8 jets, 3 b-tags)		(8 jets, $\geq$ 4 b-tags)		($\geq$ 9 jets, 3 b-tags)		($\geq$ 9 jets, $\geq$ 4 b-tags)	
	pre-fit (post-fit) yields											
Multijet	27875	(29026)	2501	(2476)	23246	(24340)	3037	(2986)	17141	(17627)	2908	(2809)
$t\bar{t}$+lf	7357	(5591)	217	(155)	5338	(3756)	235	(167)	2984	(2039)	184	(130)
$t\bar{t}$+$c\bar{c}$	2524	(2421)	147	(130)	2480	(2367)	218	(194)	2041	(1979)	232	(208)
$t\bar{t}$+b	1199	(1628)	93	(106)	1062	(1401)	125	(144)	747	(996)	117	(144)
$t\bar{t}$+2b	822	(920)	65	(76)	748	(808)	95	(102)	582	(650)	103	(115)
$t\bar{t}$+$b\bar{b}$	980	(1192)	276	(348)	1167	(1418)	481	(583)	1168	(1382)	591	(715)
Single t	511	(471)	29	(26)	350	(309)	37	(34)	211	(182)	32	(24)
V+jets	380	(327)	35	(31)	255	(213)	36	(32)	141	(117)	20	(15)
$t\bar{t}$+V	98	(87)	16	(15)	102	(87)	21	(19)	83	(75)	18	(18)
Diboson	5	(5)	0.6	(0.4)	2	(3)	0.9	(0.9)	0.3	(0.3)	0.2	(0.2)
Total bkg.	41750	(41668)	3380	(3364)	34750	(34703)	4287	(4262)	25099	(25047)	4206	(4179)
$\pm$ tot unc.	$\pm$3214	($\pm$328)	$\pm$285	($\pm$69)	$\pm$2800	($\pm$318)	$\pm$415	($\pm$82)	$\pm$2063	($\pm$289)	$\pm$451	($\pm$86)
$t\bar{t}$H	156	(223)	44	(65)	160	(224)	64	(91)	139	(191)	66	(92)
$\pm$ tot unc.	$\pm$17	($\pm$60)	$\pm$7	($\pm$17)	$\pm$19	($\pm$61)	$\pm$10	($\pm$25)	$\pm$18	($\pm$52)	$\pm$12	($\pm$25)
Data	41906		3424		34910		4351		25238		4272	

$t\bar{t}H(\rightarrow b\bar{b})$ [CMS, 2017]

SR Event Yields [2017 fit]: Single-Lepton channel (⩾6 jets, ⩾3 b-tags)

	pre-fit (post-fit) yields					
Process	$t\bar{t}$H node	$t\bar{t}$+b$\bar{b}$ node	$t\bar{t}$+2b node	$t\bar{t}$+b node	$t\bar{t}$+c$\bar{c}$ node	$t\bar{t}$+lf node
$t\bar{t}$+lf	581 (523)	232 (215)	742 (646)	608 (522)	1077 (1013)	4782 (4124)
$t\bar{t}$+c$\bar{c}$	448 (450)	256 (272)	596 (654)	326 (345)	908 (919)	1889 (2031)
$t\bar{t}$+b	313 (436)	239 (328)	435 (644)	394 (561)	266 (409)	662 (961)
$t\bar{t}$+2b	185 (199)	149 (180)	435 (467)	156 (176)	156 (198)	303 (373)
$t\bar{t}$+b$\bar{b}$	714 (902)	845 (1091)	462 (586)	295 (391)	318 (404)	470 (611)
Single t	56 (54)	62 (68)	104 (109)	46 (46)	94 (96)	209 (209)
V+jets	15 (14)	23 (22)	22 (22)	11 (11)	24 (26)	57 (59)
$t\bar{t}$+V	49 (45)	29 (26)	38 (35)	15 (15)	33 (31)	74 (68)
Diboson	0.2 (0.3)	0.7 (0.5)	0.5 (0.5)	1.0 (0.3)	0.9 (0.8)	0.5 (0.2)
Total bkg.	2362 (2625)	1835 (2203)	2834 (3165)	1853 (2066)	2877 (3095)	8447 (8436)
± tot unc.	±632 (±55)	±552 (±57)	±624 (±79)	±407 (±48)	±846 (±71)	±1871 (±135)
$t\bar{t}$H	139 (209)	41 (62)	42 (63)	23 (35)	31 (47)	65 (97)
± tot unc.	±18 (±56)	±6 (±17)	±5 (±17)	±3 (±9)	±5 (±13)	±7 (±26)
Data	2930	2253	3215	2087	3114	8538

$t\bar{t}H(\rightarrow b\bar{b})$ [CMS, 2017]

SR Event Yields [2017 fit]: Dilepton channel (⩾4 jets, ⩾2 b-tags)

	pre-fit (post-fit) yields					
Process	($\geq$ 4 jets, 2 b-tags)		($\geq$ 4 jets, 3 b-tags)		($\geq$ 4 jets, $\geq$ 4 b-tags)	
$t\bar{t}$+lf	27360	(26167)	698	(712)	7	(9)
$t\bar{t}$+$c\bar{c}$	4897	(5481)	646	(664)	20	(19)
$t\bar{t}$+b	1141	(1771)	501	(767)	24	(45)
$t\bar{t}$+2b	426	(468)	237	(286)	10	(12)
$t\bar{t}$+$b\bar{b}$	503	(634)	397	(519)	132	(177)
Single t	860	(889)	59	(63)	5	(6)
V+jets	56	(54)	7	(7)	0.1	(0.1)
$t\bar{t}$+V	248	(238)	32	(30)	6	(6)
Diboson	7	(7)	0.0	(0.0)	0.0	(0.0)
Total bkg.	35498	(35710)	2578	(3049)	206	(274)
$\pm$ tot unc.	$\pm$4714	($\pm$381)	$\pm$567	($\pm$67)	$\pm$72	($\pm$13)
$t\bar{t}$H	99	(150)	45	(68)	13	(20)
$\pm$ tot unc.	$\pm$10	($\pm$41)	$\pm$5	($\pm$17)	$\pm$2	($\pm$6)
Data	35750		3095		294	

$t\bar{t}H$ with $H \to b\bar{b}$ [2016 Data]

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

$t\bar{t}H(\rightarrow b\bar{b})$ [2016] : $t\bar{t} + \mathrm{hf}$ 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

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

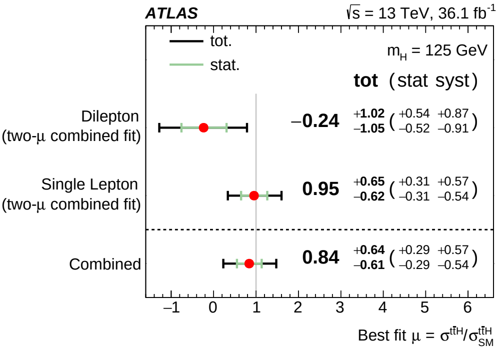
CMS

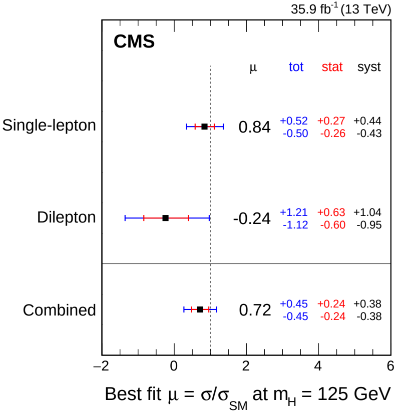
- independ. norms for all 5 $t\bar{t} + jj$ processes
  - 50% priors for $t\bar{t} + b\bar{b}$, $2b$, b, $c\bar{c}$ norms
- additional syst. from PDF, $\mu_{\mathrm{R/F}}$ scales, ISR/FSR, Tune and h_{damp} (last 3: uncorrelated across $t\bar{t} + \mathrm{hf}$ procs)
- fit model validation (no bias in $\mu_{t\bar{t}H}$):
  - 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 $t\bar{t} + b\bar{b}$

$t\bar{t}H(\rightarrow b\bar{b})$ [2016] : 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)





$t\bar{t}H(\rightarrow b\bar{b})$ [2016] : post-fit uncertainties

Breakdown of dominant systematic uncertainties

- largest systematic uncertainties on $\mu_{t\bar{t}H}$ from
  - $t\bar{t}+\mathrm{hf}$ 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
tt̄+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

$t\bar{t}H(\to b\bar{b})$ [ATLAS, 2016] : $t\bar{t}$ + hf **modeling**

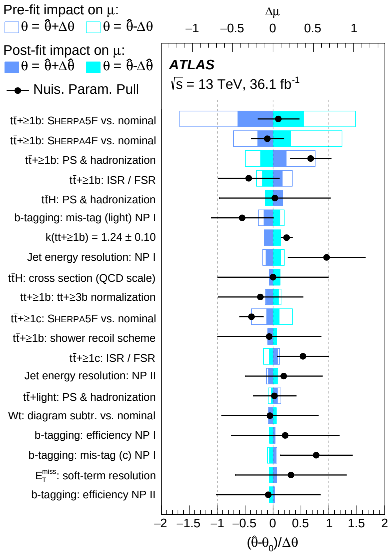
Single-Lepton and Dilepton channels

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%	$t\bar{t}+\geq 1b$

$t\bar{t}H(\to b\bar{b})$ [ATLAS, 2016] : post-fit unc. on $\mu_{t\bar{t}H}$

Single-Lepton and Dilepton channels



$t\bar{t}H(\rightarrow b\bar{b})$ [CMS, 2016] : $t\bar{t} + \mathrm{hf}$ **modeling**

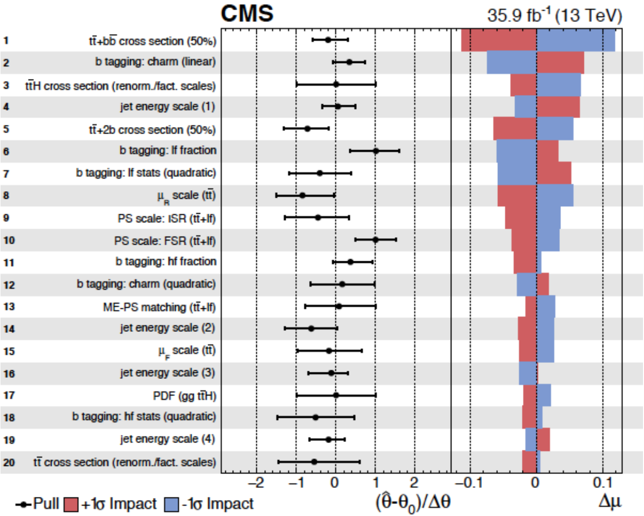
Single-Lepton and Dilepton channels

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

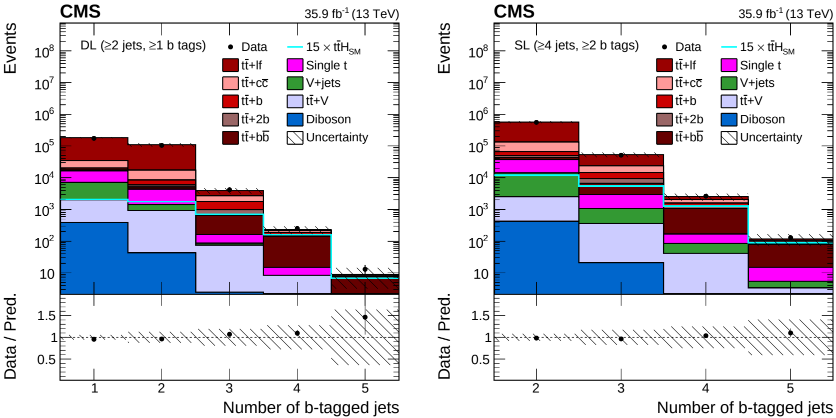
$t\bar{t}H(\to b\bar{b})$ [CMS, 2016] : post-fit unc. on $\mu_{t\bar{t}H}$

Single-Lepton and Dilepton channels



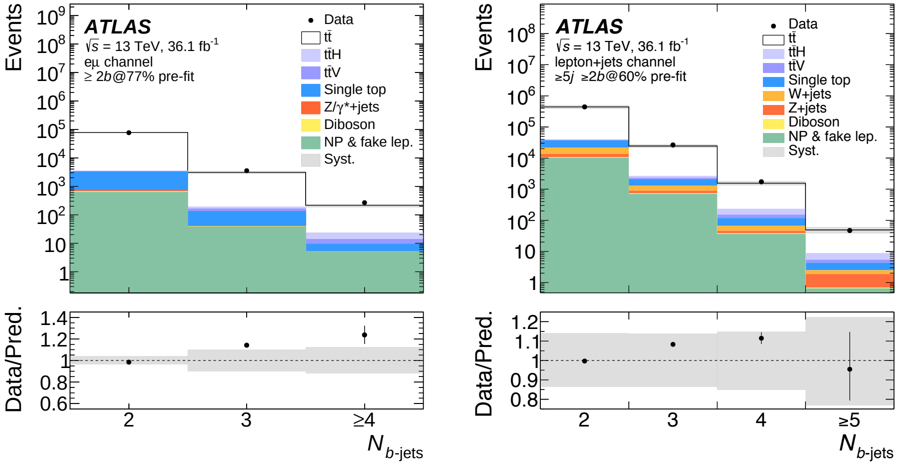
$t\bar{t}H(\rightarrow b\bar{b})$ [CMS, 2016] : number of b-tags

Single-Lepton and Dilepton channels



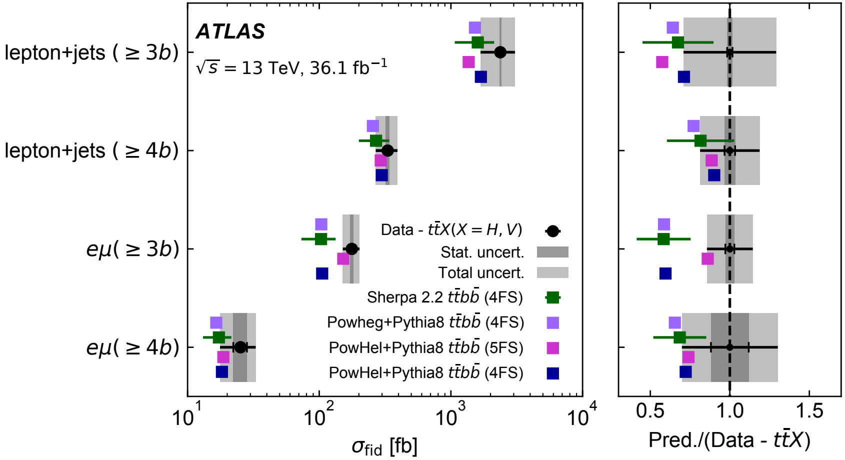
$t\bar{t} + b\bar{b}$ diff. cross sections [ATLAS, 2016] [1/3]

TOPQ-2017-12, JHEP 04 (2019) 046



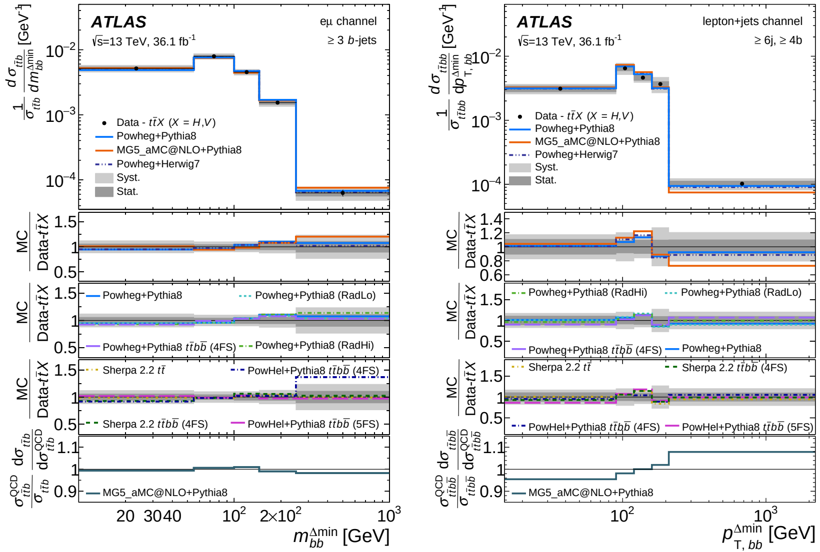
$t\bar{t} + b\bar{b}$ diff. cross sections [ATLAS, 2016] [2/3]

TOPQ-2017-12, JHEP 04 (2019) 046



$t\bar{t} + b\bar{b}$ diff. cross sections [ATLAS, 2016] [3/3]

TOPQ-2017-12, JHEP 04 (2019) 046



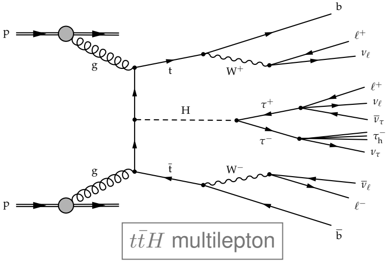
$t\bar{t}H$ observation

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

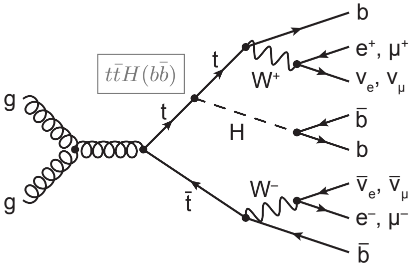
CMS : HIG-17-035, Phys. Rev. Lett. 120 (2018) 231801

$t\bar{t}H$ 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



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



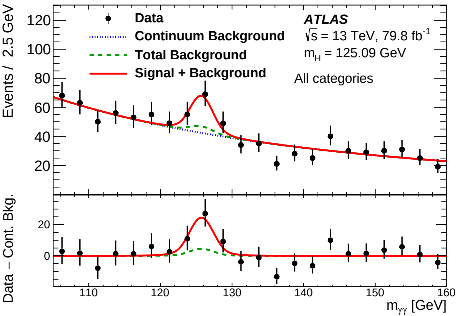
- $t\bar{t}H$ with $H \to \gamma\gamma$ and $H \to 4\ell$ decays:
  - high purity, but lowest signal yields
  - excess in inv-mass of Higgs candidate

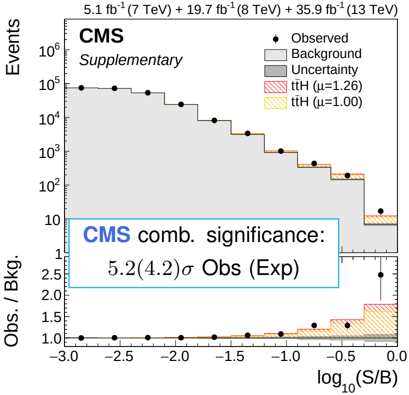
Observation of $t\bar{t}H$ production

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

- 2018: observation of $t\bar{t}H$ production by ATLAS and CMS

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





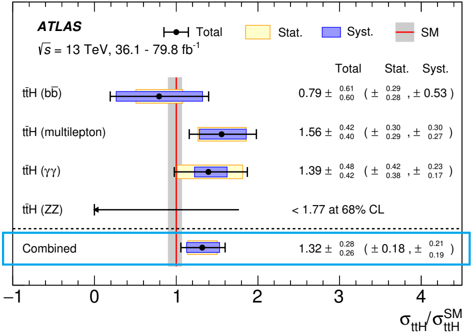
CMS comb. significance: $5.2(4.2)\sigma$ Obs (Exp)

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

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

CMS

Parameter	Best fit	Uncertainty: Stat	Uncertainty: Expt	Uncertainty: Thbgd	Uncertainty: 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 $\sim 20\%$)

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

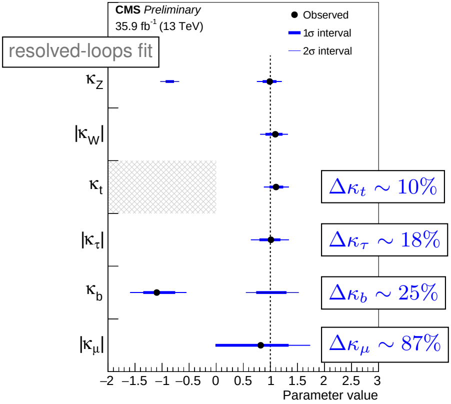
best-fit $\mu_{t\bar{t}H}$

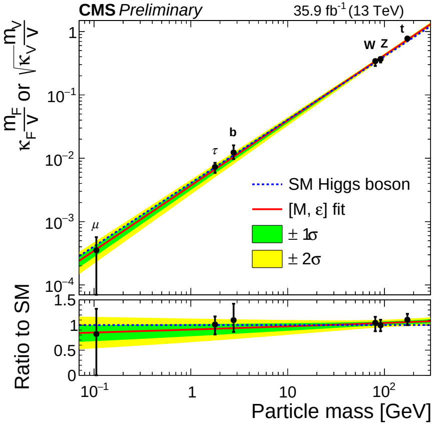
		Uncertainty			
Parameter	Best fit	Stat	Expt	Thbgd	Thsig
$\mu^{WW^*}_{t\bar{t}H}$	$1.97^{+0.71}_{-0.64}$ $\left(^{+0.57}_{-0.54}\right)$	$^{+0.42}_{-0.41}$ $\left(^{+0.39}_{-0.38}\right)$	$^{+0.46}_{-0.42}$ $\left(^{+0.36}_{-0.34}\right)$	$^{+0.21}_{-0.21}$ $\left(^{+0.17}_{-0.17}\right)$	$^{+0.25}_{-0.12}$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

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

Ref: 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.