QCD@LHC2016

Standard Model $t\bar{t}H$ Production at the LHC

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Zurich
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Motivation

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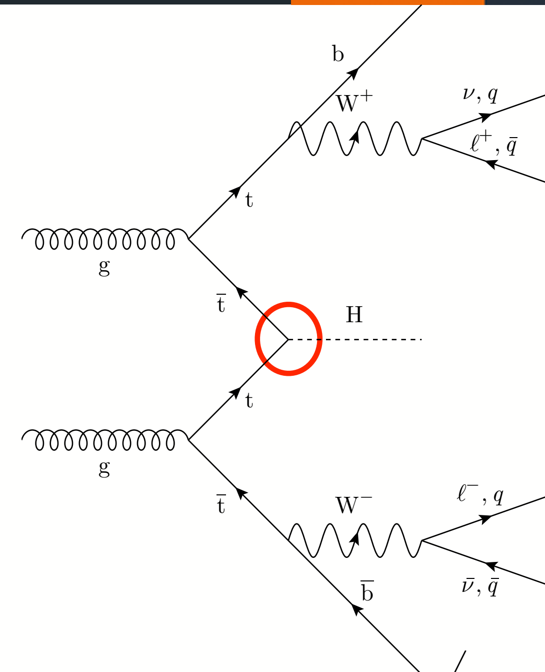
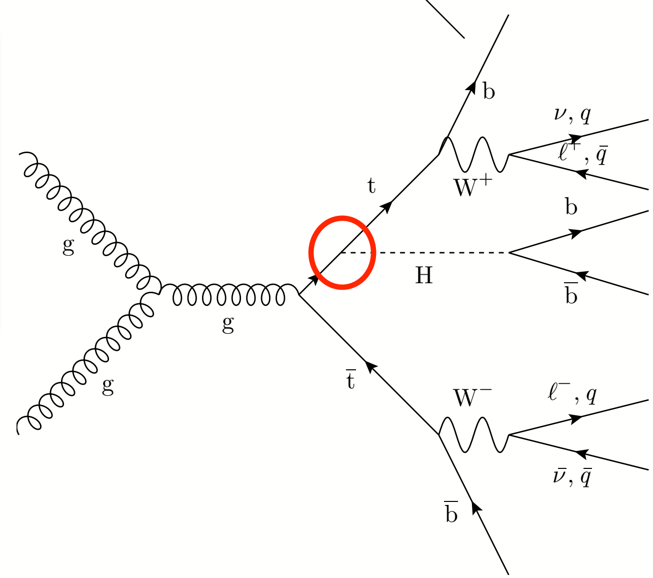
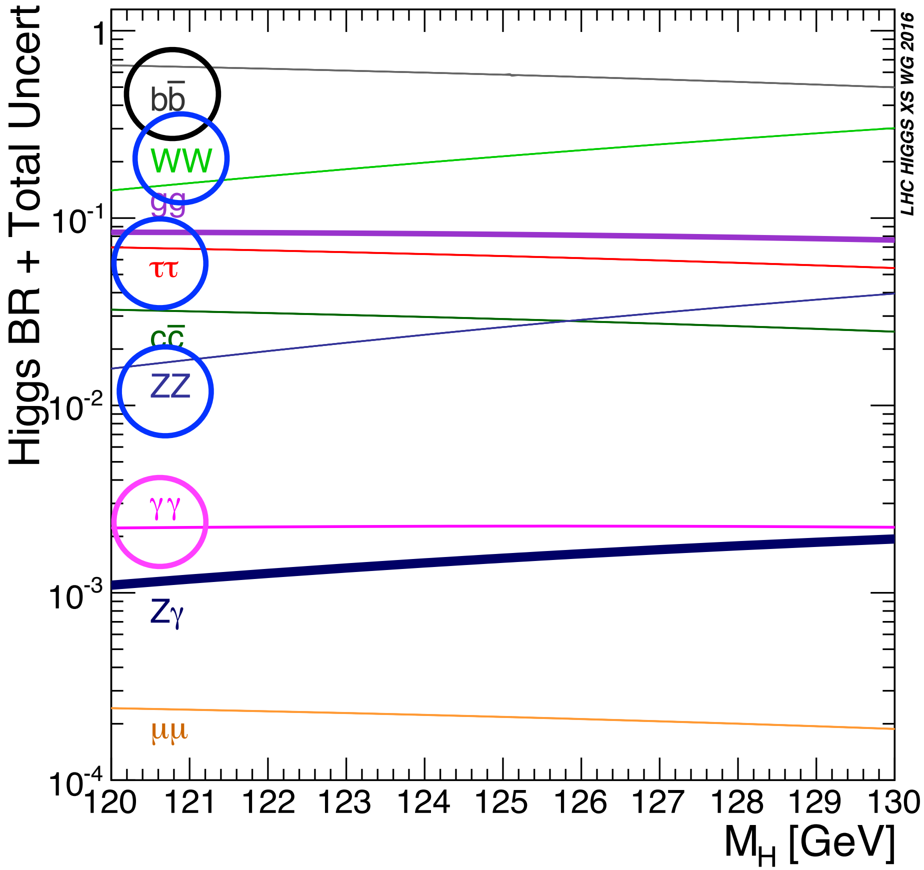
- Use **$t\bar{t}H$** events to make **direct measurement of top Yukawa coupling** (so far only probed indirectly).
- Importance:
  - Top quark **large Yukawa coupling** ($y_t \approx 1$).
  - Precise measurement can give an insight into the **energy scale of new physics**.
- Coveted measurement using **13 TeV collisions**: **enhanced cross-section**.





NLO σ (fb)	$t\bar{t}H$	$t\bar{t}$ (NNLO)	$t\bar{t}W$	$t\bar{t}Z$
8 TeV	133	2.53×10^5	232	206
13 TeV	507	8.32×10^5	566	760
13TeV/8TeV	3.8	3.3	2.4	3.7

$t\bar{t}H$ Searches



Branching Ratio (%)				
H→bb	H→$\tau\tau$	H→ZZ	H→WW	H→$\gamma\gamma$
58.1%	6.3%	2.6%	21.5%	0.23%

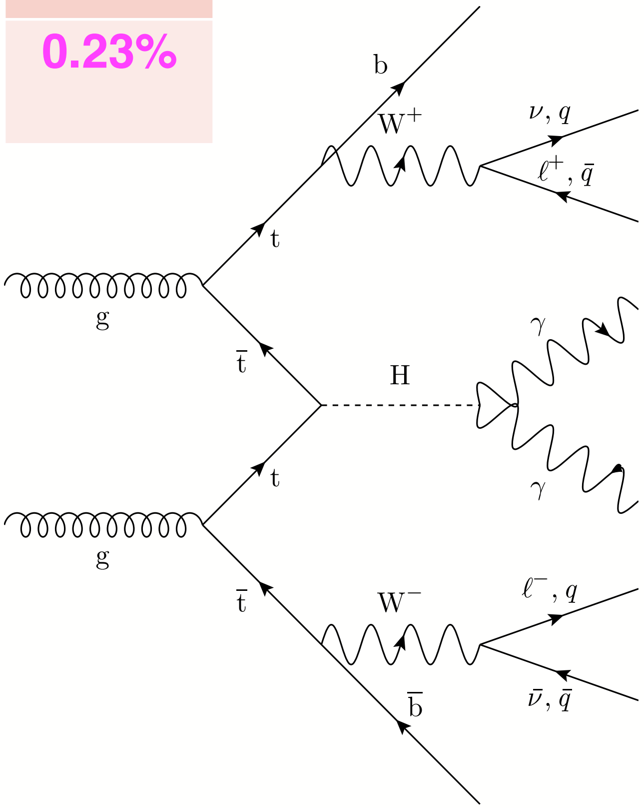
- **$t\bar{t}H$ production = relatively low x-section (1% of total Higgs production).**
- Searches preformed in **multiple Higgs decay channels.**
- **3 analyses: $t\bar{t}H(\gamma\gamma)$, $t\bar{t}H$(bb), $t\bar{t}H$(WW), $t\bar{t}H(\tau\tau)$,$t\bar{t}H$(ZZ) (i.e. multilepton).**
- **Presented today:**
  - All **ATLAS** results use **13.2-13.3 fb^{-1}.**
  - Results from **CMS $t\bar{t}H(\gamma\gamma)$** and **$t\bar{t}H$(multilepton)** using **12.9 fb^{-1}.**
  - Results from **CMS $t\bar{t}H$(bb)** and combination using **2.3-2.7 fb^{-1}.**

$t\bar{t}H(\gamma\gamma)$ - Introduction

ATLAS-CONF-2016-067

- **Clean signal** - excellent diphoton mass resolution.
- **Narrow $M(\gamma\gamma)$ peak on smoothly falling (continuum) background.**
- Although **small BR,** high γ reconstruction and ID efficiency → at relatively large luminosities, **relatively large signal yield**.

$H\rightarrow\gamma\gamma$
0.23%



ATLAS $t\bar{t}H(\gamma\gamma)$ - Event Selection

ATLAS-CONF-2016-067

- **≥2 tight isolated photons:** lead(sublead) photon $E_T/m_{\gamma\gamma}$ >0.35(0.25).
- **105 GeV < $M_{\gamma\gamma}$ < 160 GeV**.

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

- **≥ 1 lepton** > 15GeV
- **≥2 jets** > 25 GeV.
- **≥ 2 b-tagged jets or ≥1 b-tagged jet + missing E_T** > 20 GeV.
- Veto 84 GeV < **Inv. $M_{e\gamma}$ (M_{ll})** < 94 GeV reduces Z+jets and ZH.

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

- **== 0 leptons** and **≥ 5 jets** with p_T > 30 GeV.
- **≥ 1 b-tagged jet**.

Channel	Region	$t\bar{t}H$ (S)	Bkgd (B)	$tHjb + WtH$	S/B	N_{Data}
$H \to \gamma\gamma$	all-hadronic	1.58	8.27	0.10	0.19	9
	leptonic	1.16	2.42	0.10	0.48	2

Diphoton mass interval:

- all-hadronic: 121.9 - 127.9 GeV
- leptonic: 121.9 - 127.8 GeV

ATLAS $t\bar{t}H(\gamma\gamma)$ - Signal and Background

ATLAS-CONF-2016-067

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

- Signal $M(\gamma\gamma)$ distribution modelled using a **double-sided crystal ball function.**
- **Model parameters** that define the shape are **determined from fit** to simulated $H\rightarrow\gamma\gamma$ sample (aMcatNLO +Pythia8).

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

- Background $M(\gamma\gamma)$ distribution modelled using **exponential function**.
- **Functions shape and normalisation are obtained from fit to data in sidebands**.
- Uncertainty associated with choice of function.

ATLAS $t\bar{t}H(\gamma\gamma)$ - Results

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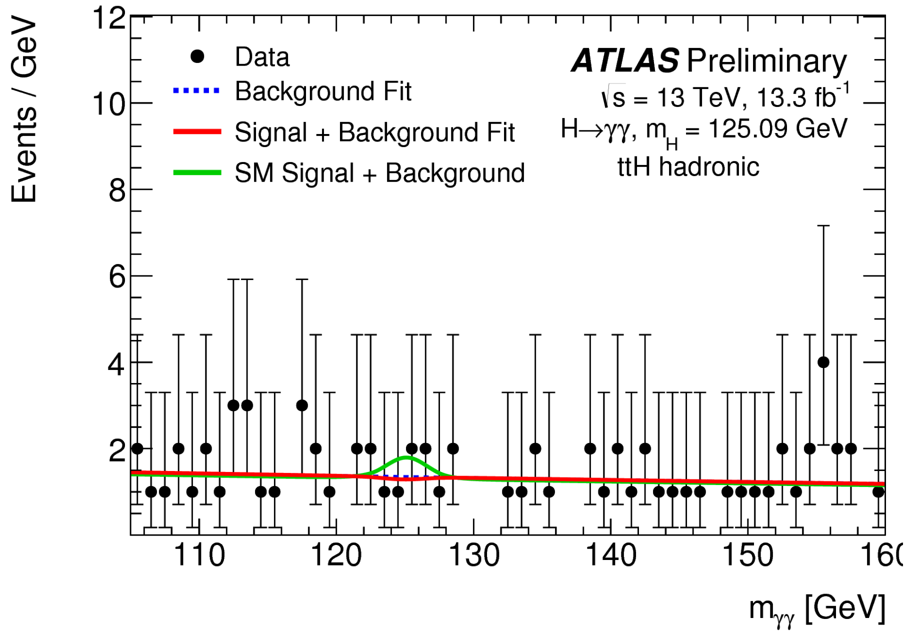
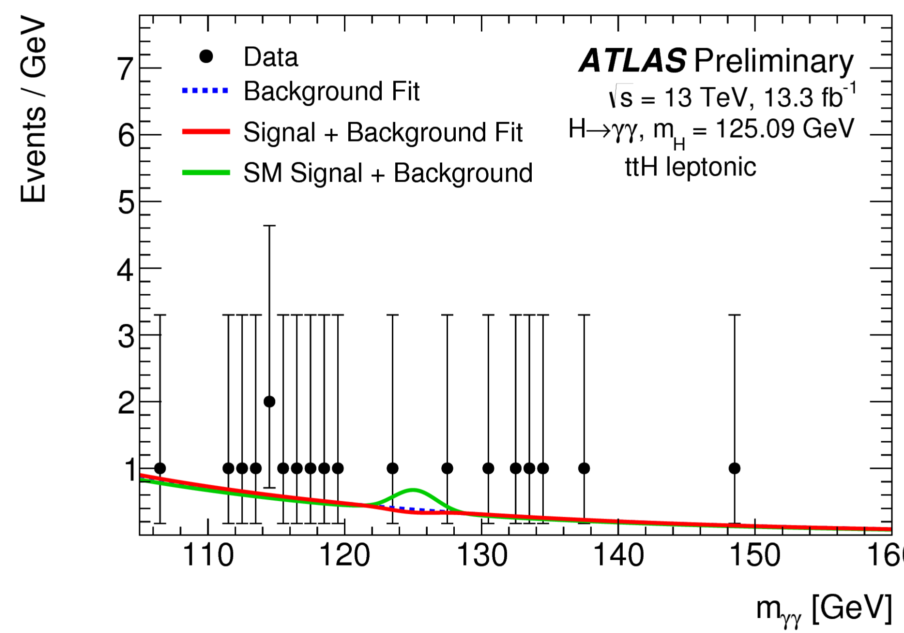
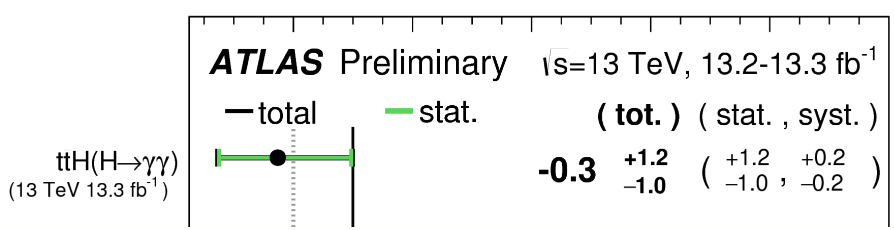
- Un-binned maximum likelihood fit of S+B $M(\gamma\gamma)$ spectrum model to data performed to extract signal.
- Green line: expected S+B $M(\gamma\gamma)$ spectrum given predicted SM signal.
- Red line: observed S+B $M(\gamma\gamma)$ spectrum given fitted signal strength parameter.







- Best fit value of the signal strength from $t\bar{t}H$ combination.
- Statistically dominated uncertainty.

CMS $t\bar{t}H(\gamma\gamma)$ - Event Selection

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CMS PAS HIG-16-020

- **2 isolated photons:** Lead (sub-lead) photon p_T > 30(20) GeV.
- Lead(sub-lead) photon $p_T/m_{\gamma\gamma}$ > 0.5(0.25).
- **100 GeV < $M_{\gamma\gamma}$ < 180 GeV**.

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

- **≥1 lepton** (e,μ) away from Z peak p_T > 20 GeV.
- **≥2 jets** p_T > 25 GeV.
- **≥1 b-tagged jet**.
- **Pass loose requirement of $BDT_{\gamma\gamma}$** (trained to give high score to signal-like events).

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

- **==0 leptons**.
- **≥5 jets** p_T > 25 GeV.
- **≥1 b-tagged jets**.
- **Pass minimum value of $BDT_{\gamma\gamma}$ output** (balance between significance optimisation and need of a number of events to fit the background).

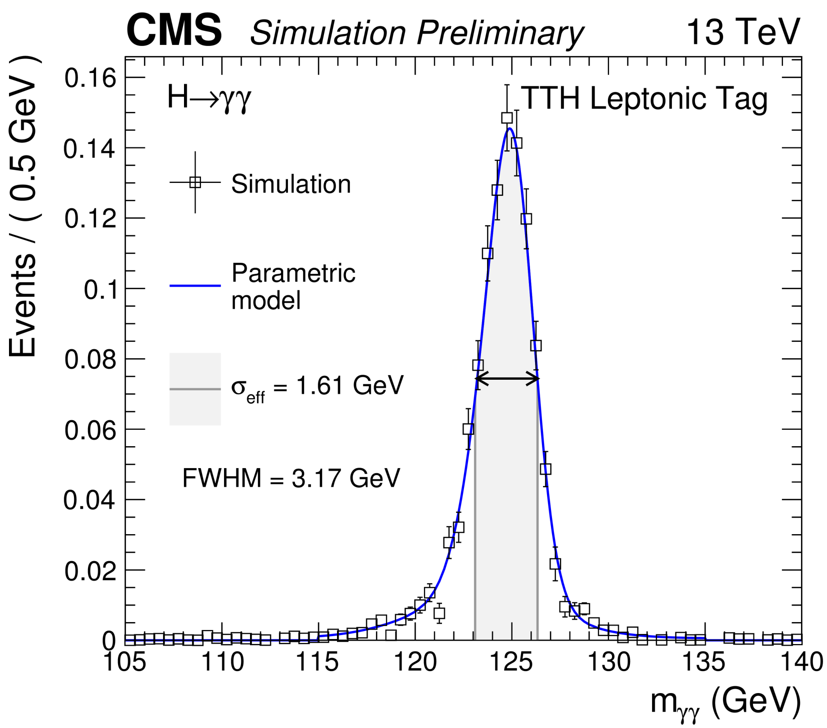
CMS $t\bar{t}H(\gamma\gamma)$ - Signal and Background

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

- **Signal described by analytic function (sum of ≤5 Gaussians).**
- **Function fit to simulated M($\gamma\gamma$) distribution.**
- **Model is constructed by interpolating each parameter between 7 individual mass points using spline.**
- Corrected for relevant efficiencies in data.

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

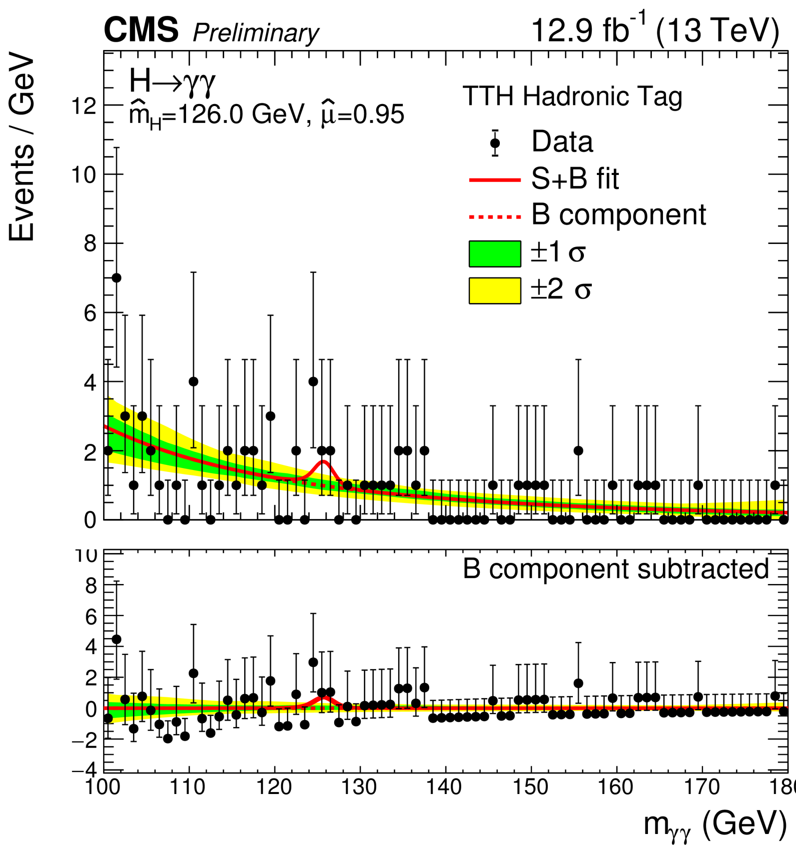
- **Background also described by analytic function.**
- **Background model extracted from data using the discrete profiling method (arXiv).**
- Choice of background function treated as discrete parameter in likelihood fit to data.
- Systematic uncertainty associated with choice of analytic function.

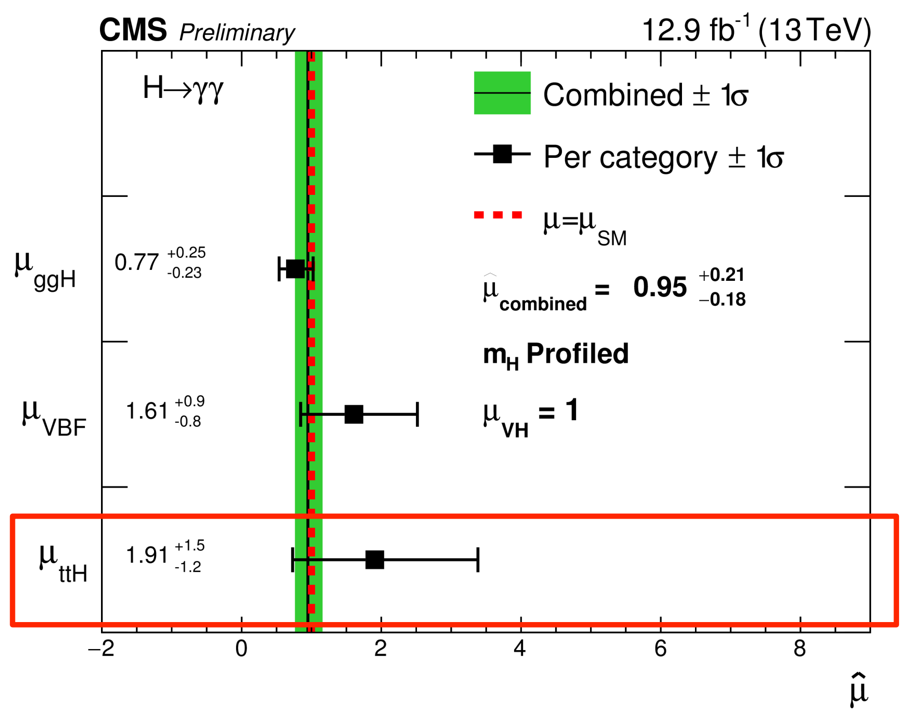


- Fitted signal shape for signal sample simulated with a M_H=125 GeV

CMS $t\bar{t}H(\gamma\gamma)$ - Results

- **S+B model fit to data for each category.**
- **Best fit value of $\mu_{t\bar{t}H(\gamma\gamma)}$ = 1.91**
- Uncertainty **statistically dominated.**
- The $t\bar{t}H(\gamma\gamma)$ signal strength reported in context of $H\rightarrow\gamma\gamma$ combination.



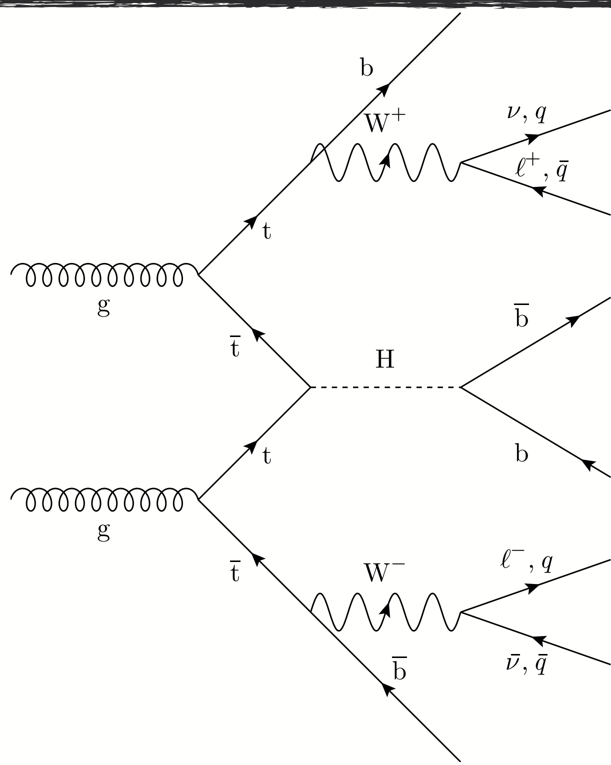


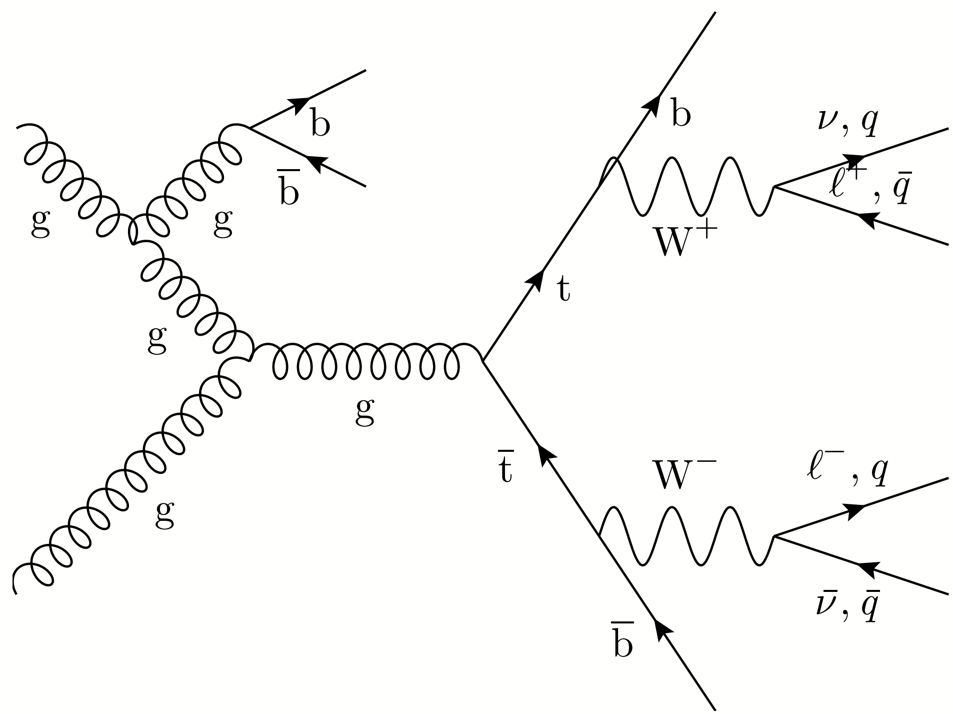
ATLAS-CONF-2016-080

CMS PAS HIG-16-004

- H→bb = **largest branching fraction** for 125 GeV Higgs Boson.
- **Probes bottom Yukawa coupling**.
- **Challenging $t\bar{t}$ background**.
- Large irreducible background from $t\bar{t}$+≥1b.

H → bb
58.1%





ATLAS $t\bar{t}H(bb)$ - Event Selection

$t\bar{t}H(bb)$ Single Lepton

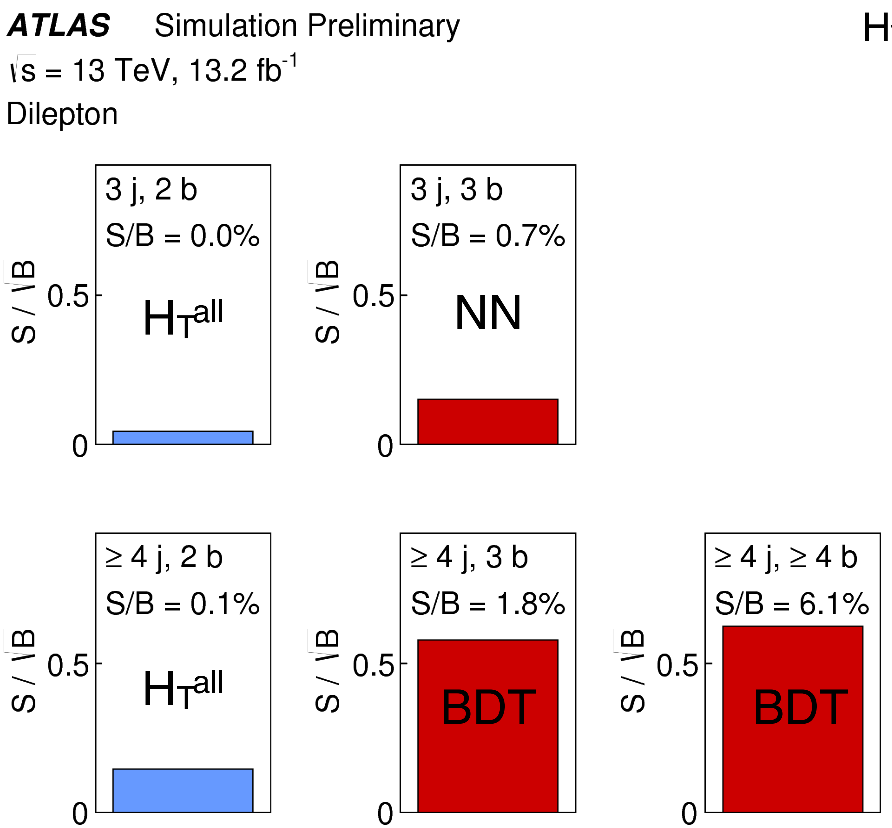
- **== 1** tight **lepton** with pT ≥ 25 GeV
- **≥ 4 jets** with pT ≥ 25 GeV
- **≥ 2 b-jets**

$t\bar{t}H(bb)$ Dilepton

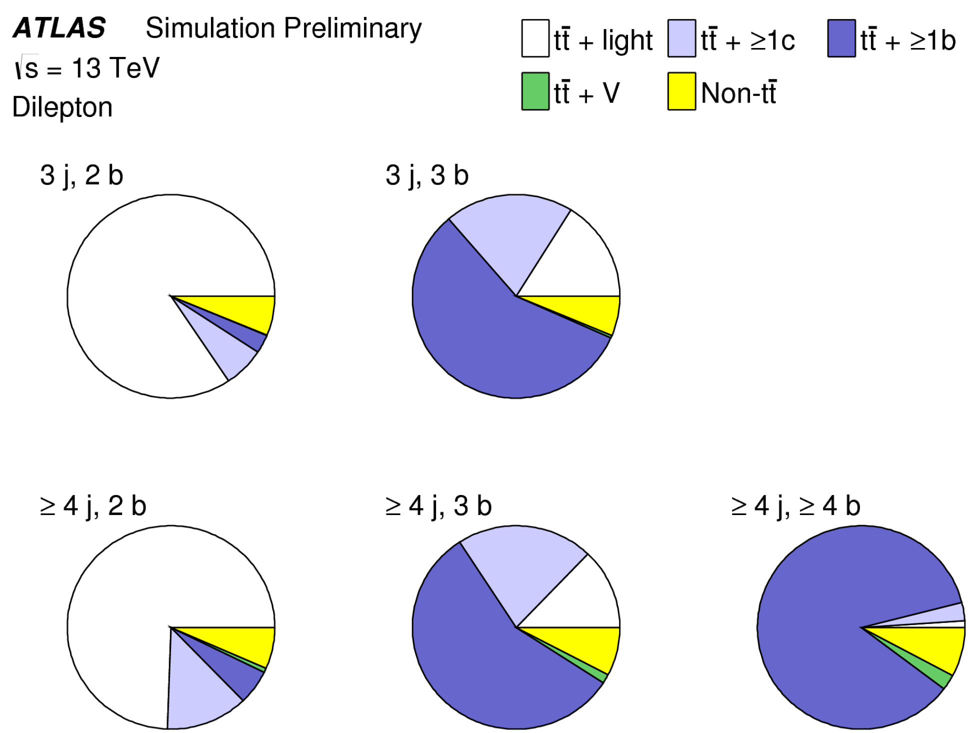
- **== 2 tight leptons**:
  - Leading lepton pT ≥ 25 GeV
  - Subleading lepton pT ≥ 15GeV electrons, 10 GeV Muons
- **≥ 3 jets** w. pT ≥ 25 GeV
- **≥ 2 b-jets.**
- **M_{ll} > 15 GeV**
- e^+e^- and $\mu^+\mu^-$ channels:
  - **Z mass window cut**: 83 GeV < M_{ll} < 99 GeV

ATLAS $t\bar{t}H(bb)$ - Analysis Regions

- **Events categorised according to # b-jets and # jets.**
- **Signal rich** regions provide **most sensitivity**.
- **Signal depleted** regions - help to **constrain systematic uncertainties**.
- **Single discriminant distribution constructed in each region.**
- **Simultaneously fit discriminants in all regions to data and extract signal.**

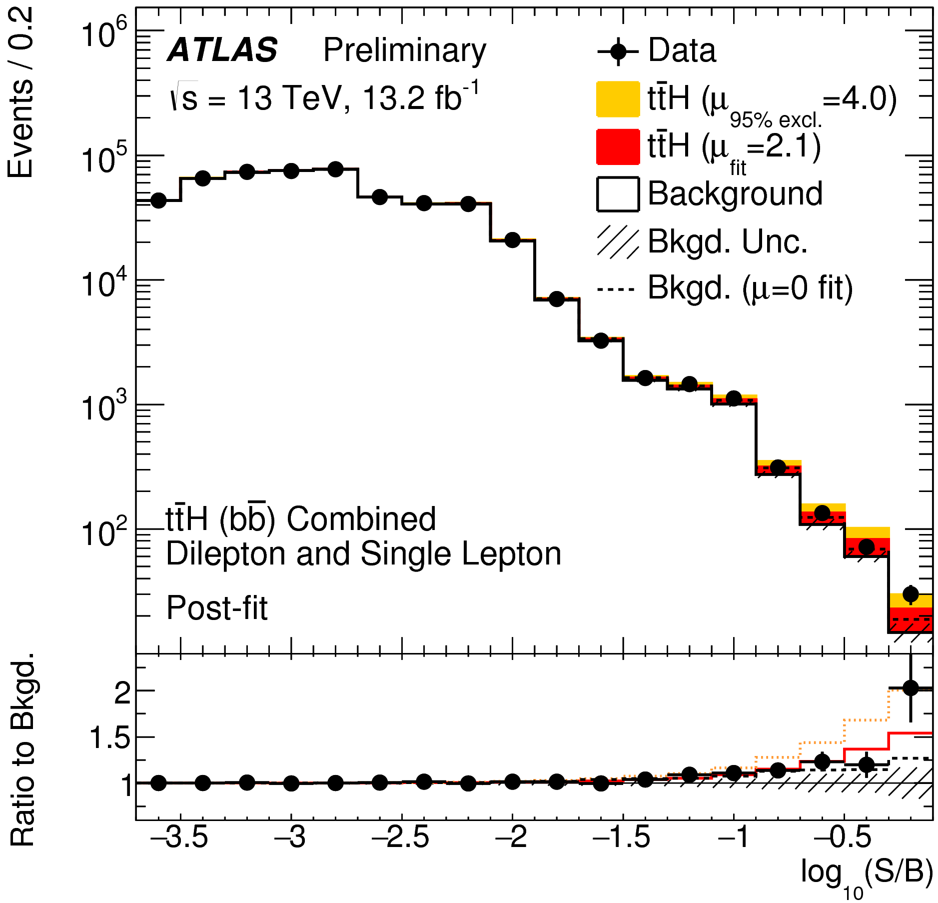


$H_T^{all(had)}$ = scalar sum p_T of all (hadronic) objects event.

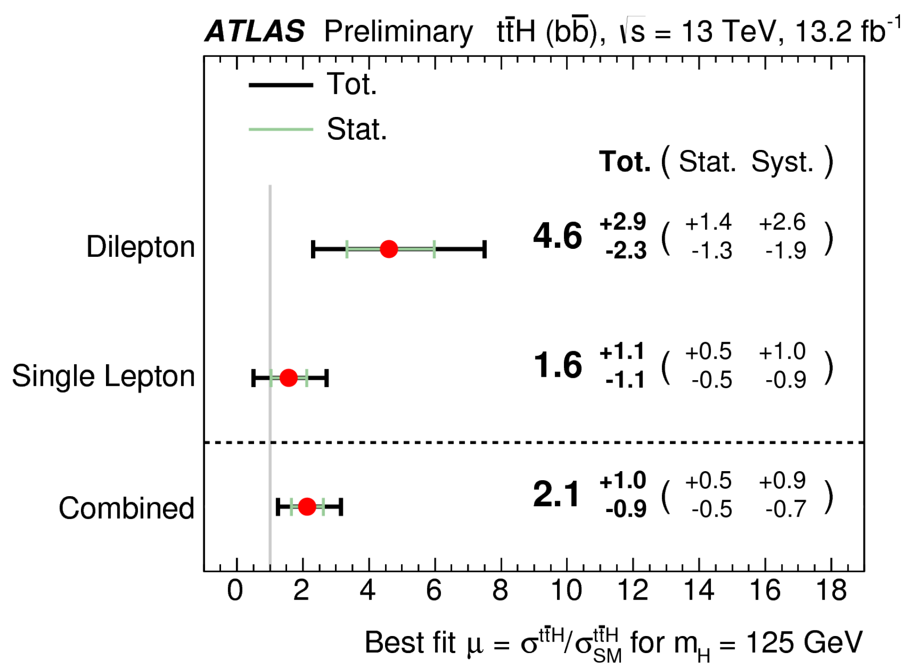


ATLAS $t\bar{t}H(bb)$ - Results

- **Data vs post-fit prediction** in all bins used in analysis, **ranked in terms of S/B**.



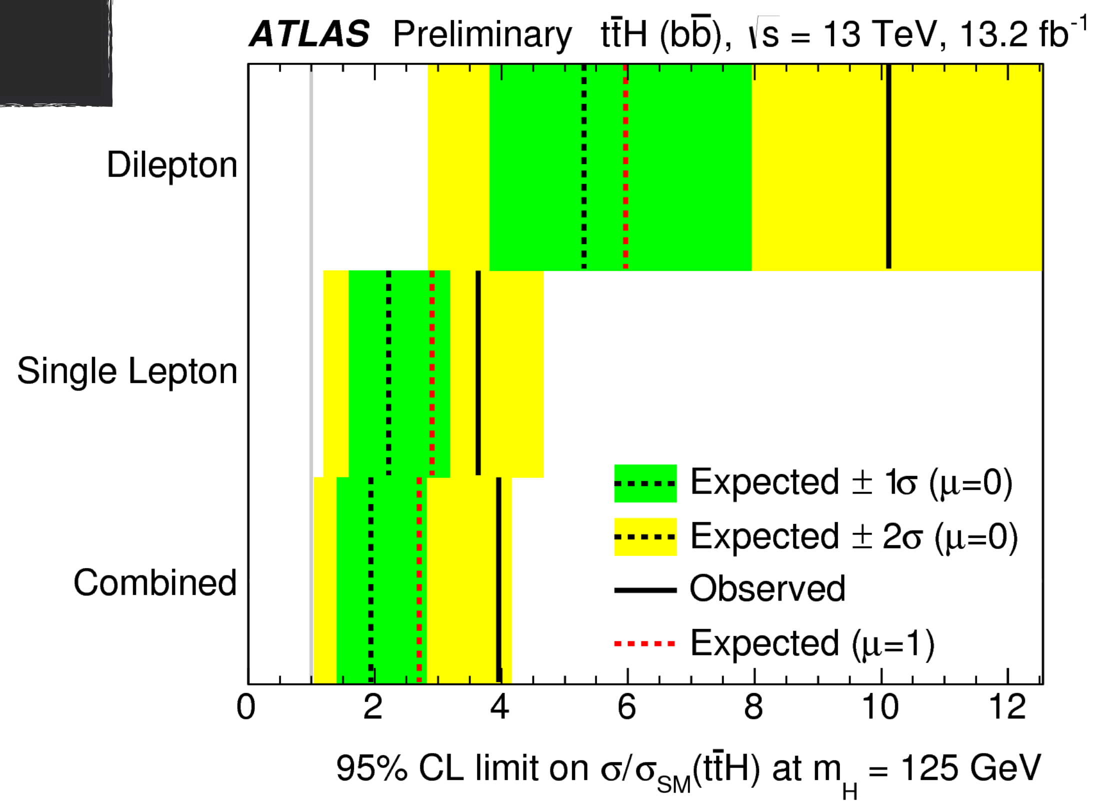
- **No significant deviation from the SM $t\bar{t}H$ prediction is seen.**
- Uncertainty is systematically dominated.



ATLAS $t\bar{t}H(bb)$ - Results

	Observed	Expected ($\mu = 0$) Median	+/-1σ	+/-2σ	Expected ($\mu = 1$)
Dilepton	10.1	5.3	[3.8, 7.9]	[2.8, 12.6]	6.0
Single lepton	3.6	2.2	[1.6, 3.2]	[1.2, 4.7]	2.9
Combined	4.0	1.9	[1.4, 2.8]	[1.0, 4.2]	2.7

- **95% CL upper limits on $t\bar{t}H(bb)$ signal strength parameter.**



CMS $t\bar{t}H(bb)$ - Event Selection

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CMS PAS HIG-16-004

Single Lepton

- **== 1 isolated μ (e)** > 25 (30) GeV.
- **≥4 jets** > 30 GeV.
- **≥2 b-tagged jets**.
- **Boosted category: Must have a reconstructed boosted hadronic top and Higgs candidate** p_T > 200 GeV.

Dilepton

- **== 2 OS isolated leptons** lead(sublead) > 20(15) GeV.
- **≥3 jets** with p_T > 20 GeV (2 of which must have p_T > 30 GeV).
- **≥2 b-tagged jets**.
- **M_{ll} > 20 GeV** (suppress HF resonance decays and low-mass Drell-Yann).
- e^+e^- and $\mu^+\mu^-$ channels:
  - Veto **76 GeV < M_{ll} < 106 GeV** (surpress Z+jets).
  - **MET > 40 GeV**

* "Boosted objects": High p_T objects where decay products become highly collimated and can cluster into a single jet.

CMS $t\bar{t}H(bb)$ - Analysis Regions

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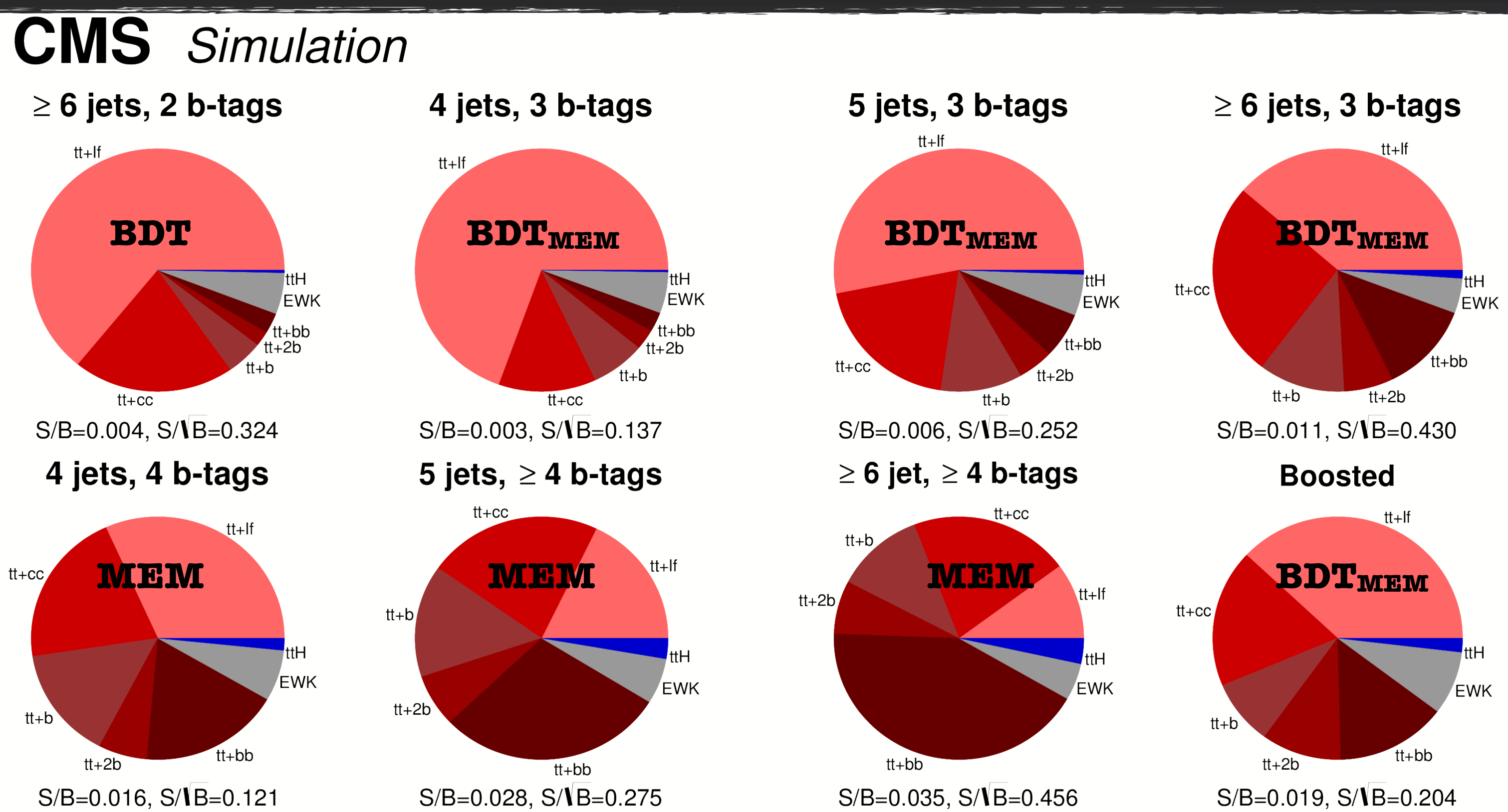
CMS PAS HIG-16-004

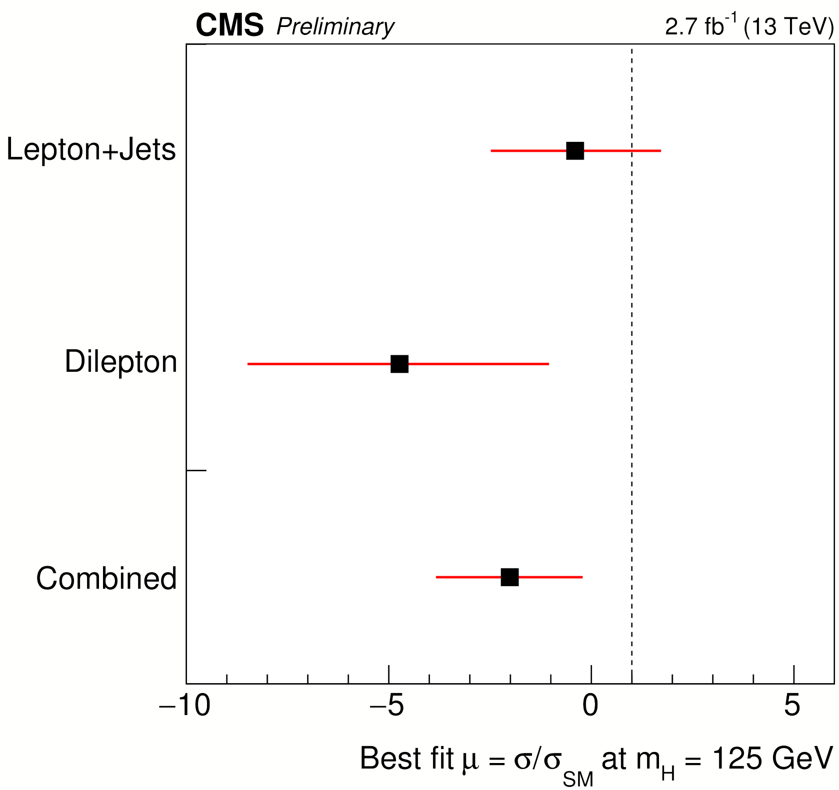
- **Events categorised by # jets & # b-tagged jets (separate boosted category).**
- **Single discriminant distribution constructed in each region.**
- Either **BDT or Matrix Element Method.**
- **Simultaneously fit discriminants in all regions to data** and extract signal.



CMS $t\bar{t}H(bb)$ - Results

CMS PAS HIG-16-004

Channel	Best-fit μ
Lepton+jets	$-0.4^{+2.1}_{-2.1}$
Dilepton	$-4.7^{+3.7}_{-3.8}$
Combined	$-2.0^{+1.8}_{-1.8}$

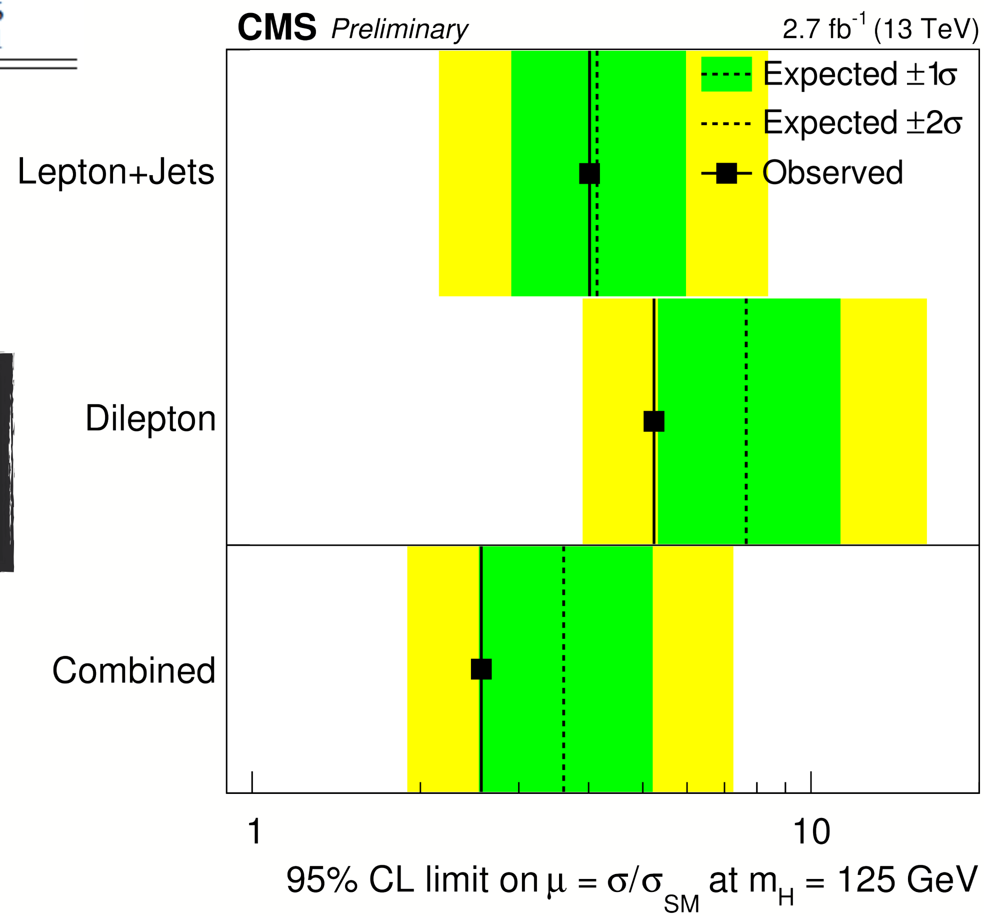


- **Observed μ is 1.7σ from SM prediction (μ=1).**
- **No significant deviation from the background only hypothesis is observed either.**

CMS $t\bar{t}H(bb)$ - Results

Channel	Best-fit μ	Observed UL	Expected UL
Lepton+jets	$-0.4^{+2.1}_{-2.1}$	4.0	$4.1^{+1.8}_{-1.2}$
Dilepton	$-4.7^{+3.7}_{-3.8}$	5.2	$7.7^{+3.6}_{-2.3}$
Combined	$-2.0^{+1.8}_{-1.8}$	2.6	$3.6^{+1.6}_{-1.1}$

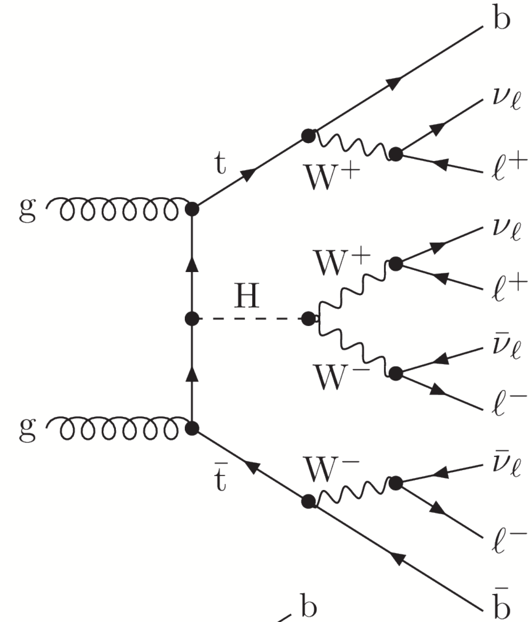
- **Observed (expected) 95% confidence level upper limit of 2.6 (3.6).**



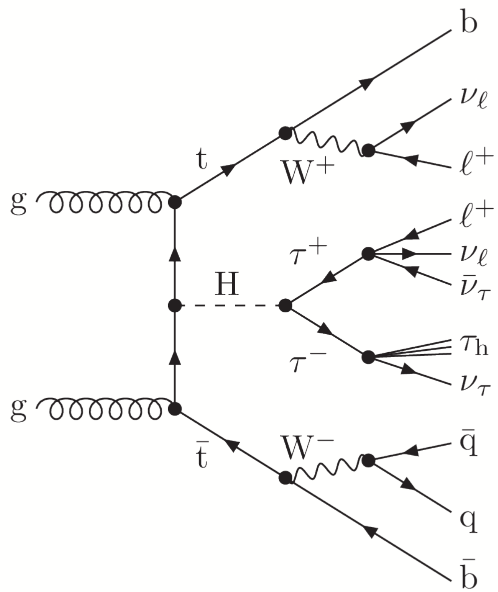
$t\bar{t}H(WW^{(*)},ZZ^{(*)},\tau\tau)$ - Introduction

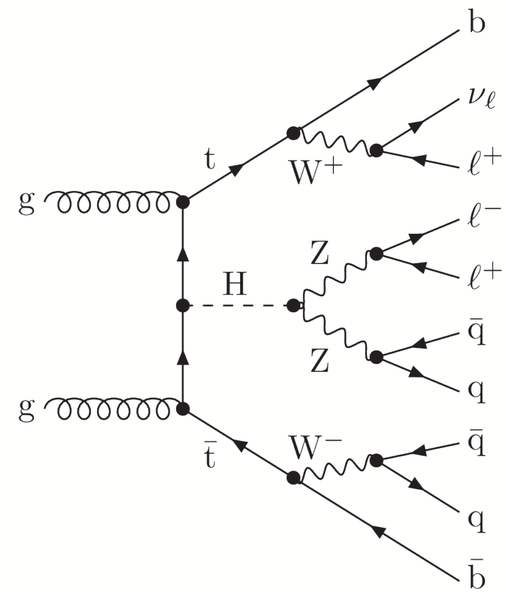
ATLAS-CONF-2016-058

- **Several multilepton signatures**: Higgs decaying to either vector bosons or τ-leptons.
- **Clean signatures.**
- Effective at **suppressing the $t\bar{t}$** background.
- Backgrounds include:
    - **Electron charge mis-reconstruction.**
    - **Non-prompt lepton.**
    - **$t\bar{t}W$, $t\bar{t}Z$, diboson.**
    - **τ_{had} mis-reconstruction.**



$H\rightarrow\tau\tau$	$H\rightarrow ZZ$	$H\rightarrow WW$
6.3%	2.6%	21.5%





ATLAS $t\bar{t}H(WW^{(*)},ZZ^{(*)},\tau\tau)$ - Event Selection

ATLAS-CONF-2016-058

$2\ell 1\tau_{had}$

- **2 SS leptons 1 τ_{had}.**
- **≥ 4 jets.**
- **≥1 b-tagged jet.**

3ℓ

- **3 leptons** (e,μ)
- **≥ 4 jets & ≥ 1 b-tagged jet**
- **OR ≥ 3 jets & ≥ 2 b-tagged jets**

$2\ell 0\tau_{had}$

- **2 SS leptons NO τ_{had}.**
- **≥ 5 jets.**
- **≥ 1 b-tagged jet.**

4ℓ

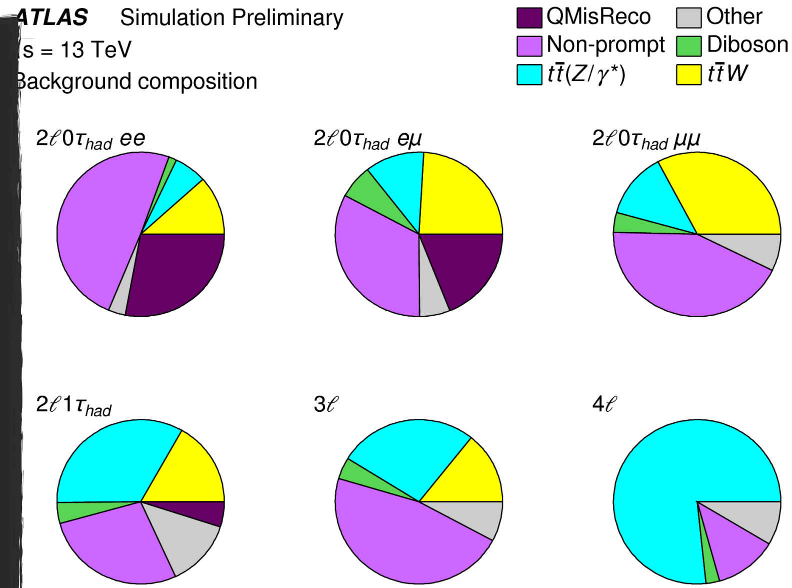
- **4 leptons** (e,μ)
- **≥ 2 jets.**
- **1 b-tagged jet**

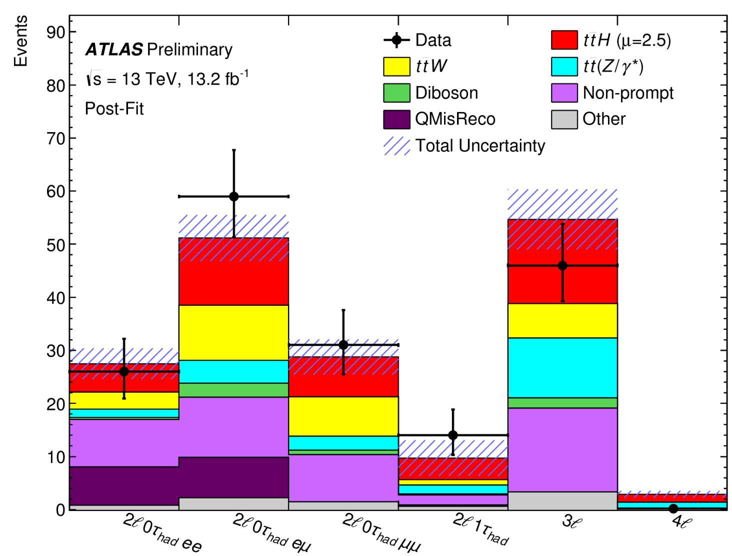
	Higgs boson decay mode				$A \times \epsilon$
Category	WW^*	$\tau\tau$	ZZ^*	Other	$(\times 10^{-4})$
$2\ell 0\tau_{had}$	77%	17%	3%	3%	14
$2\ell 1\tau_{had}$	46%	51%	2%	1%	2.2
3ℓ	74%	20%	4%	2%	9.2
4ℓ	72%	18%	9%	2%	0.88

ATLAS $t\bar{t}H(WW^{(*)},ZZ^{(*)},\tau\tau)$ - Signal & Backgrounds

ATLAS-CONF-2016-058

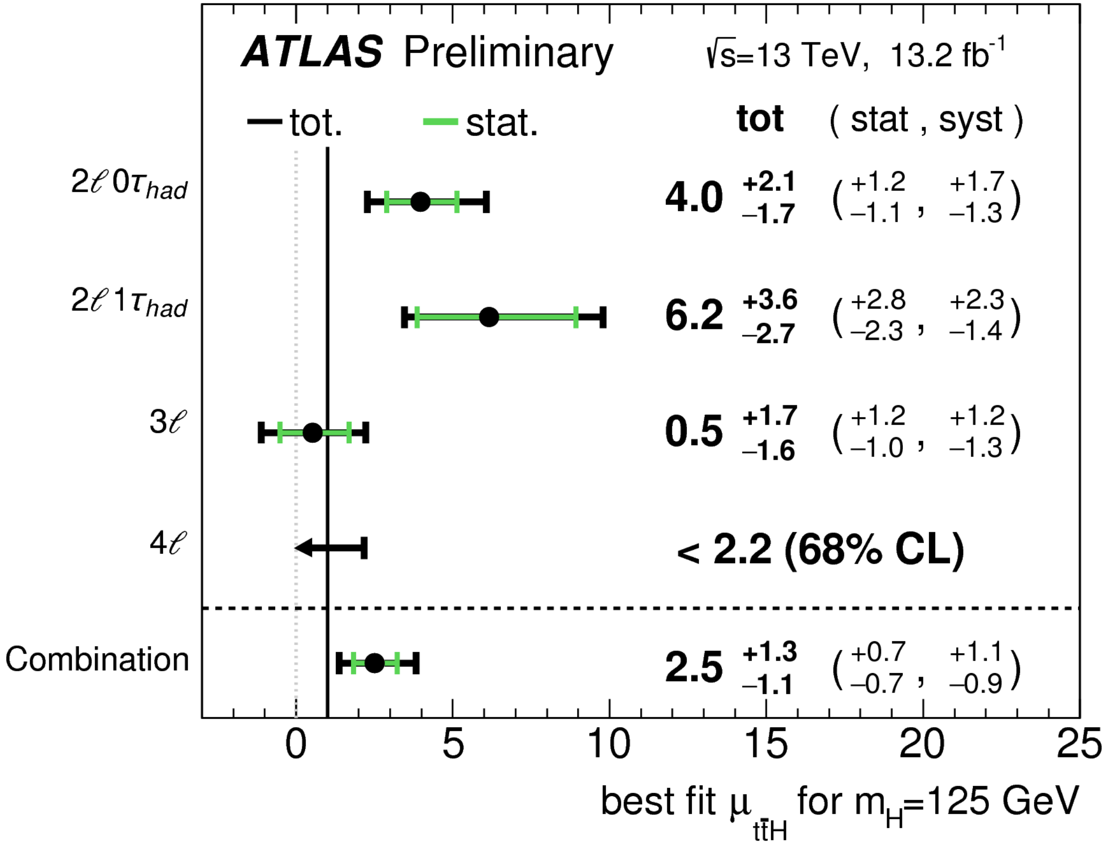
- $t\bar{t}H$(multilepton) signal prediction taken from simulation.
- **$t\bar{t}W$, $t\bar{t}Z$, diboson backgrounds with prompt leptons** estimated from simulation and studied in control regions.
  - Allows check of # events and jet multiplicity modelling.
- All the other backgrounds are estimated using data-driven methods.
- **# expected events** is simultaneously fit to data in each of the 6 analysis regions to extract the signal.





ATLAS $t\bar{t}H(WW^{(*)},ZZ^{(*)},\tau\tau)$ - Results

- Best fit values of $\mu_{t\bar{t}H}$ **show no significant deviation from SM expectation.**
- **Systematic uncertainty dominated by non-prompt background estimates.**
- 4ℓ category, zero events are observed so a 68% CLs upper limit is shown instead.



ATLAS $t\bar{t}H(WW^{(*)},ZZ^{(*)},\tau\tau)$ - Results

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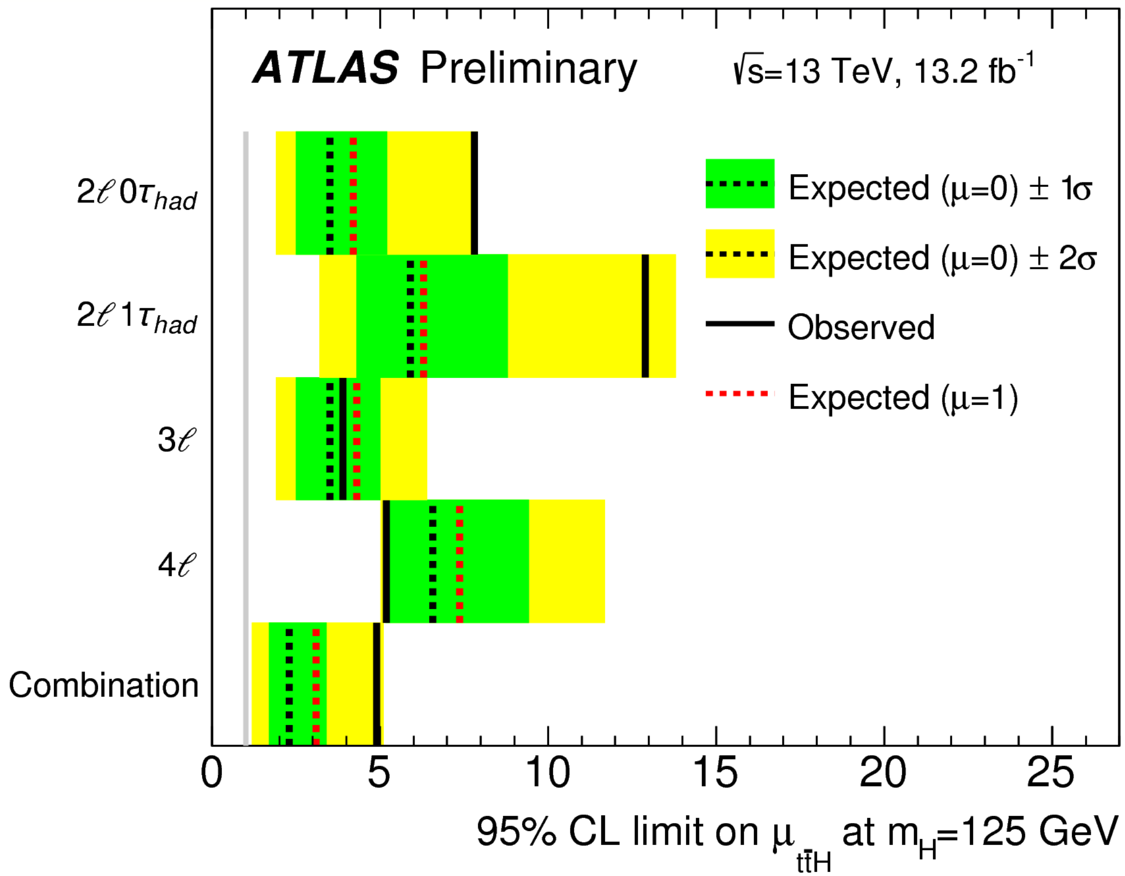
ATLAS-CONF-2016-058

- Expected 95% CL upper limit set under S+B (B only) hypothesis in dashed red (dashed black).
- Observed 95% CL upper limit for combined $\mu_{t\bar{t}H(\mathrm{multilepton})}$ = **4.9.**



CMS $t\bar{t}H(WW^{(*)},ZZ^{(*)},\tau\tau)$ - Event Selection

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3ℓ

- **≥3 tight leptons** with Z veto.
- **M_{ll} > 12 GeV** (< 12GeV not well modelled).
- **≥2 jets.**
- **≥2 loose or ≥1 medium b-tagged.**

2ℓSS

- **==2 SS tight leptons**: lead(sublead) electrons > (25)15 GeV).
- **M_{ll} > 12 GeV** (< 12GeV not well modelled).
- **Z mass veto.**
- ≥ **4 jets.**
- **≥2 loose or ≥1 medium b-tagged.**

	$\mu\mu$	ee	eμ	3ℓ
$t\bar{t}W$	18.3 ± 0.9	6.8 ± 0.6	24.5 ± 1.1	12.2 ± 0.7
$t\bar{t}Z/\gamma^*$	5.8 ± 0.6	7.4 ± 0.6	15.3 ± 1.3	22.6 ± 1.0
Di-boson	1.4 ± 0.2	1.1 ± 0.2	2.6 ± 0.3	5.7 ± 0.4
tttt	0.8 ± 0.2	0.4 ± 0.1	1.5 ± 0.2	1.2 ± 0.1
tqZ	0.2 ± 0.3	0.4 ± 0.4	0.6 ± 0.6	2.7 ± 0.8
Rare SM bkg.	1.6 ± 0.3	0.5 ± 0.1	1.8 ± 0.1	0.3 ± 0.1
Charge mis-meas.		6.7 ± 0.1	10.0 ± 0.1	
Non-prompt leptons	33.4 ± 1.2	23.1 ± 1.1	61.9 ± 1.7	51.0 ± 1.8
All backgrounds	61.5 ± 1.7	46.4 ± 1.5	118.0 ± 2.5	95.7 ± 2.3
$t\bar{t}H$ ($H \to WW^*$)	6.3 ± 0.2	2.6 ± 0.1	8.5 ± 0.2	8.0 ± 0.2
$t\bar{t}H$ ($H \to \tau\tau$)	1.6 ± 0.1	0.7 ± 0.1	2.5 ± 0.1	2.1 ± 0.1
$t\bar{t}H$ ($H \to ZZ^*$)	0.2 ± 0.0	0.1 ± 0.0	0.3 ± 0.0	0.5 ± 0.0
Data	74	45	154	105

CMS PAS HIG-16-022

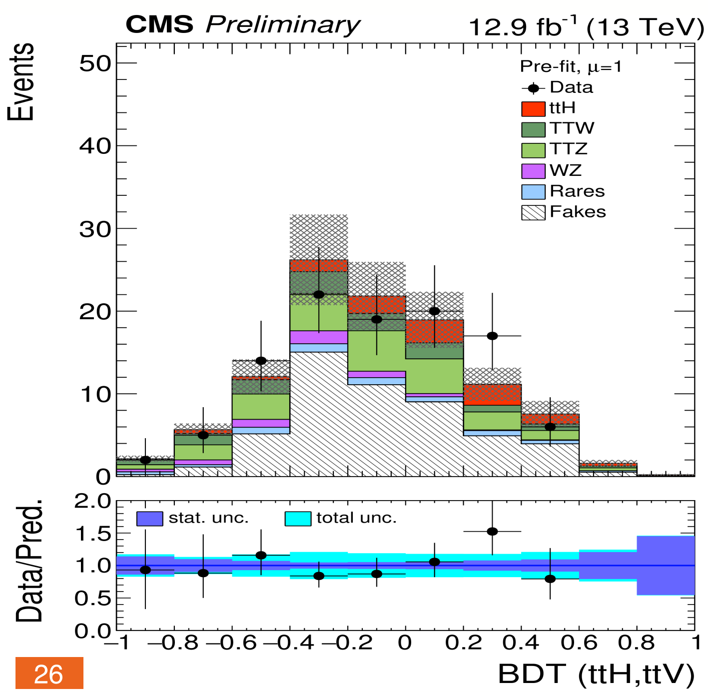
- **"Tight" leptons if they pass a given lepton BDT threshold.**
- BDT trained to give high score to prompt signal leptons low score to non-prompt/fake leptons.

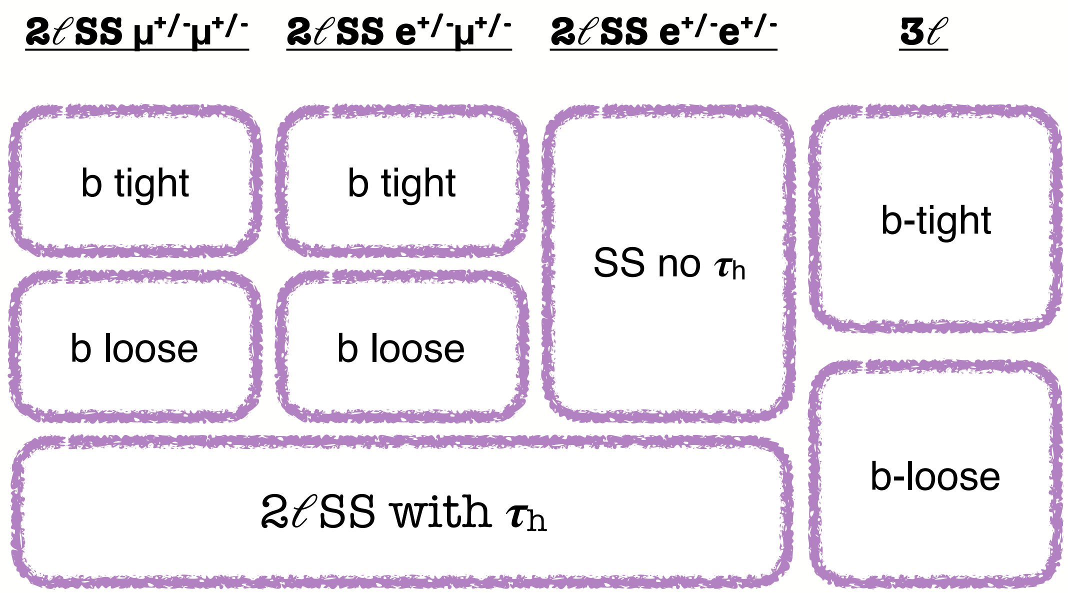
CMS $t\bar{t}H(WW^{(*)},ZZ^{(*)},\tau\tau)$ - Analysis Regions/Extraction

CMS PAS HIG-16-022

- 2 BDTs trained in each region:
  - 1 against $t\bar{t}$ and another against $t\bar{t}V$ which are then combined.
  - BDT output divides categories into single bins of different S/B.

- **Simultaneous fit to data** → extract signal by fitting its normalisation among these bins.





CMS $t\bar{t}H(WW^{(*)},ZZ^{(*)},\tau\tau)$ - Results

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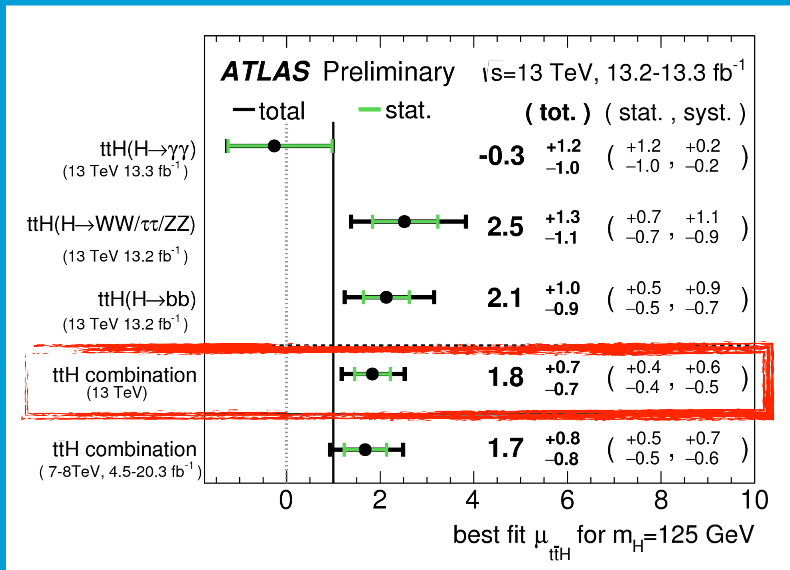
CMS PAS HIG-16-022

Category	Obs. limit	Exp. limit $\pm 1\sigma$	Best fit μ $\pm 1\sigma$
Same-sign dileptons	4.6	$1.7^{+0.9}_{-0.5}$	$2.7^{+1.1}_{-1.0}$
Trileptons	3.7	$2.3^{+1.2}_{-0.7}$	$1.3^{+1.2}_{-1.0}$
Combined categories	3.9	$1.4^{+0.7}_{-0.4}$	$2.3^{+0.9}_{-0.8}$
Combined with 2015 data	3.4	$1.3^{+0.6}_{-0.4}$	$2.0^{+0.8}_{-0.7}$

- Reported **95% CL upper limit** on signal production cross-section = **3.4** x SM.
- Expected **95% CL upper limit under the B only** hypothesis = **1.3**.
- Combined **best-fit μ = 2.0.**

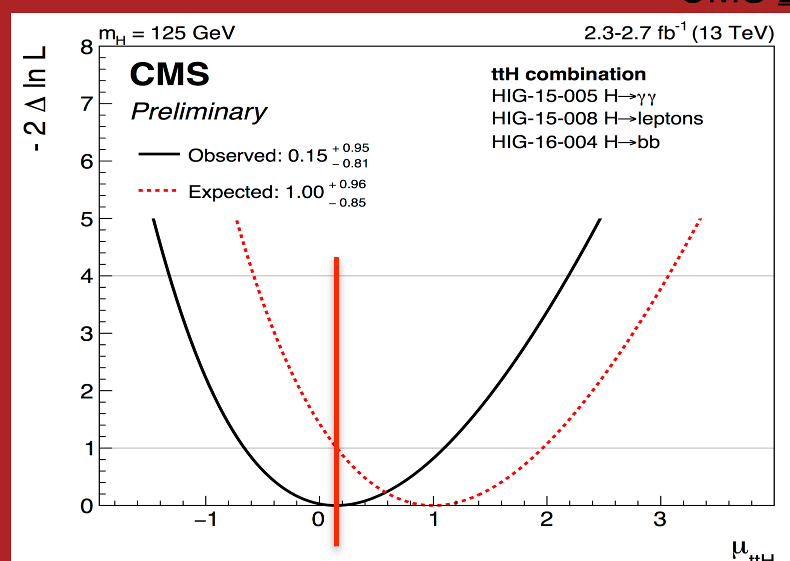
$t\bar{t}H$ Combination

ATLAS-CONF-2016-068



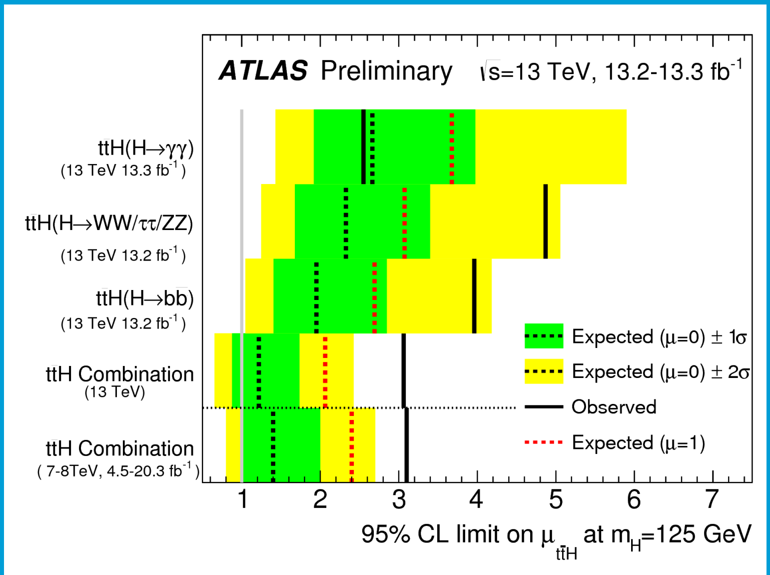
Channel	Significance	
	Observed [σ]	Expected [σ]
$t\bar{t}H,\ H\to\gamma\gamma$	-0.2	0.9
$t\bar{t}H,\ H\to(WW,\tau\tau,ZZ)$	2.2	1.0
$t\bar{t}H,\ H\to b\bar{b}$	2.4	1.2
ttH combination	2.8	1.8

CMS 2016 Combination (2015 data)



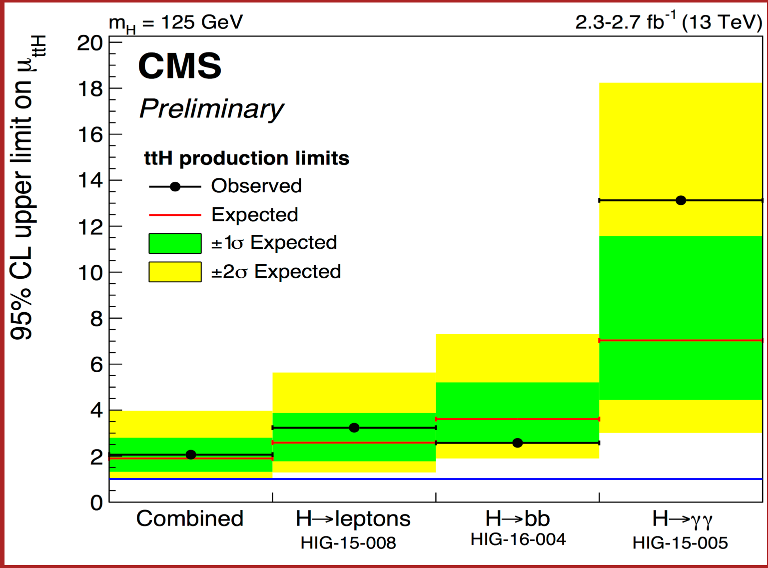
$t\bar{t}H$ Combination

ATLAS-CONF-2016-068



Analysis	Observed	$-2\ \sigma$	$-1\ \sigma$	Median ($\mu_{t\bar{t}H}=0$)	$+1\ \sigma$	$+2\ \sigma$	Median ($\mu_{t\bar{t}H}=1$)
$t\bar{t}H,\ H\to\gamma\gamma$	2.6	1.4	1.9	2.7	4.0	5.9	3.7
$t\bar{t}H,\ H\to(WW,\tau\tau,ZZ)$	4.9	1.2	1.7	2.3	3.4	5.1	3.1
$t\bar{t}H,\ H\to b\bar{b}$	4.0	1.0	1.4	1.9	2.8	4.2	2.7
$t\bar{t}H$ combination	3.0	0.6	0.9	1.2	1.7	2.4	2.1
$t\bar{t}H$ combination Run-1	3.1	0.8	1.0	1.4	2.0	2.7	2.4

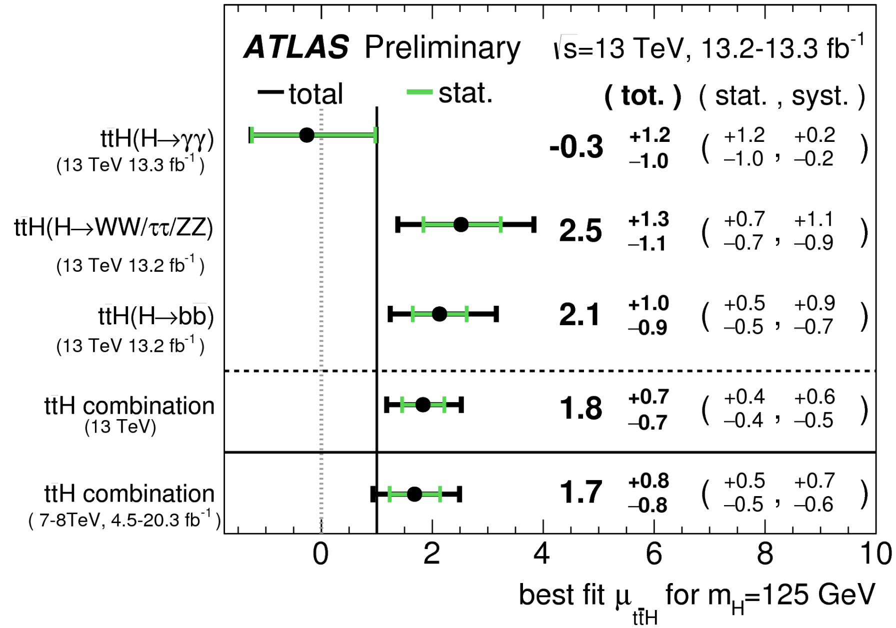
CMS 2016 Combination (2015 data)



Combined observed (expected S+B) 95% CL upper limit on $\mu_{t\bar{t}H}$ = 2.1 (1.9)

Summary

- Results for **$t\bar{t}H(\gamma\gamma)$**, **$t\bar{t}H(bb)$**, **$t\bar{t}H$(multilepton)** and the $t\bar{t}H$ combination analyses using **13.2-13.3 fb^{-1}** presented by **ATLAS**.
- Results for **$t\bar{t}H(\gamma\gamma)$** and **$t\bar{t}H$(multilepton)** using **12.9 fb^{-1}** along with the **$t\bar{t}H(bb)$ and combination** results using **2.3 - 2.7 fb^{-1}** presented by **CMS**.
- Combined **ATLAS $\mu_{t\bar{t}H}$ = 1.8** which corresponds to an observed significance of 2.8σ (sensitivity **exceeds that of 7-8 TeV** analysis of 1.5σ).
- **Expect improved precision using full 2016 dataset from both experiments.**



CMS	μ (2.3 - 2.7 fb^{-1})	μ (12.9 fb^{-1})
multilepton	$0.6^{+1.4}_{-1.1}$	$2.0^{+0.8}_{-0.7}$
$\gamma\gamma$	$3.8^{+4.5}_{-3.6}$	$1.91^{+1.5}_{-1.2}$
bb	$-2.0^{+1.8}_{-1.8}$	
Combination	$0.15^{+0.95}_{-0.81}$	

Backup

ATLAS $t\bar{t}H(\gamma\gamma)$ - Signal Modelling

- Signal manifests as narrow peak in $M_{Inv}(\gamma\gamma)$ spectrum.
- Narrow width of Higgs boson means the shape is very dependant on the resolution of measured photon energies.
- Functional form for signal model (double sided CB or CB+Gauss) chosen by:
  - Comparing the shape.
  - Fitting both with injected signal and measuring bias.
- Using double sided CB.
- Non-Gaussian contributions to mass resolution - electron from converted photon looses energy via bremsstrahlung in the inner detector.
- Signal shape fitted separately for leptonic and hadronic.
- Shape systematics - NP can be pulled towards a favourable mass or resolution when fitting to data.
- Yields = product of X-section and BR (YR4 with M_H = 125.09 Gev), selection efficiency using all Higgs samples (ggH, WH, tH, ttH etc.) with M_H = 125 GeV and luminosity.
- 90% ttH signal.
- Selection efficiency using m_H = 125 GeV sample - 0.01% change in efficiency expected when changing from 125 GeV - 125.9 GeV.

ATLAS $t\bar{t}H(\gamma\gamma)$ - Background Composition

- Dominant = SM continuum diphoton production.
- Also significant: γj and jj since energetic π^0's from jet fragmentation can fake photons.
- <1% from Drell-Yann where both electrons fake photons.
- # events from each background source related to photon and/or jet efficiencies for passing photon ID and isolation requirements - determined from simulation.
- Systematic uncertainties on efficiencies propagated - give uncertainty on background composition in SR.

	Yield ± stat. ± syst.			Fraction ± stat. ± syst. [%]		
	$\gamma\gamma$	γ-jet	jet-jet	$\gamma\gamma$	γ-jet	jet-jet
ttH hadronic	$30 \pm 21\ ^{+0}_{-18}$	$1 \pm 1\ ^{+19}_{-1}$	$0 \pm 0\ ^{+1}_{-0}$	$97.5 \pm 4.7\ ^{+0.4}_{-60.6}$	$2.2 \pm 4.5\ ^{+59.4}_{-2.3}$	$0.4 \pm 0.5\ ^{+4.6}_{-0.4}$
ttH leptonic	$9 \pm 7\ ^{+1}_{-9}$	$0 \pm 2\ ^{+6}_{-1}$	$1 \pm 1\ ^{+3}_{-1}$	$87.1 \pm 27.7\ ^{+5.6}_{-87.3}$	$4.3 \pm 20.0\ ^{+55.7}_{-6.1}$	$8.6 \pm 16.8\ ^{+31.6}_{-8.7}$

Channel	Region	$t\bar{t}H$ (S)	Bkgd (B)	$tHjb + WtH$	S/B	N_{Data}
$H \to \gamma\gamma$	all-hadronic	1.58	8.27	0.10	0.19	9
	leptonic	1.16	2.42	0.10	0.48	2

ATLAS $t\bar{t}H(\gamma\gamma)$ - Signal and Background

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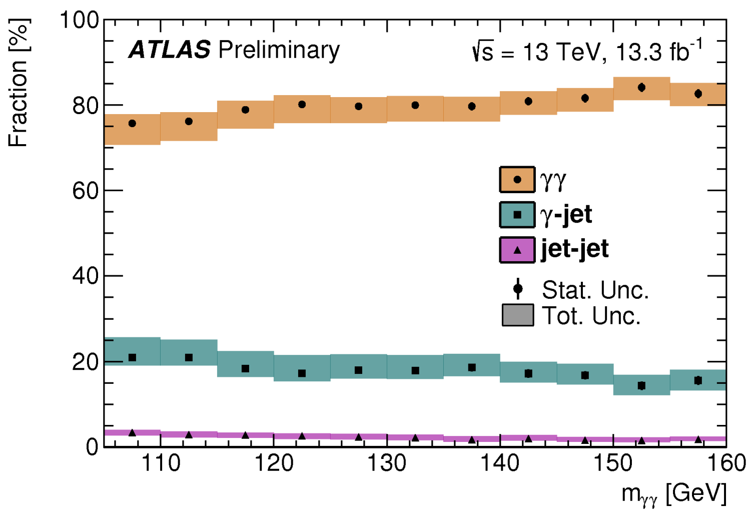
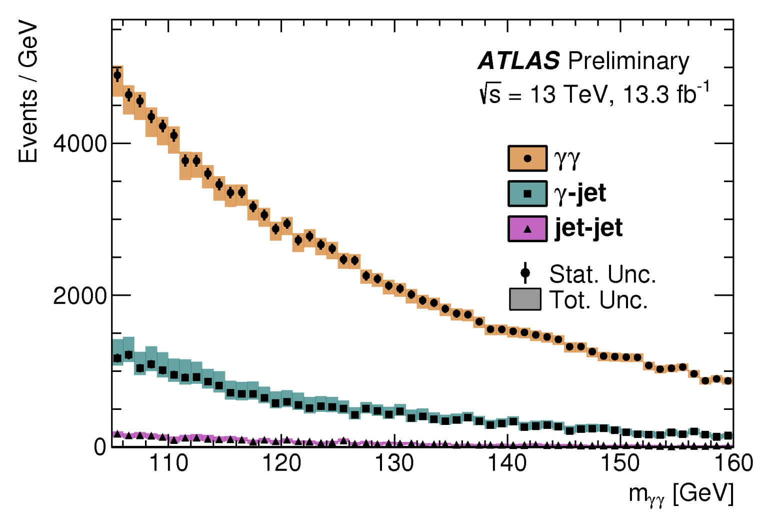
$t\bar{t}H(\gamma\gamma)$ Signal

- Signal manifests as **narrow peak in $M_{Inv}(\gamma\gamma)$ spectrum**.
- $t\bar{t}H$ signal modelled using **aMcAtNlo+Pythia8**: M_H = 125 GeV with NLO x-section.
- **Double-sided Crystal Ball** with M_H = 125.09 GeV.
- **Model parameters** that define $M_{Inv}(\gamma\gamma)$ signal shape **determined from fit** to simulated $H \rightarrow \gamma\gamma$ sample.

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

- **Main backgrounds**: $\gamma\gamma$, γj and jj
- **Data-driven background measurement**.
- Composition studied in side-bands reversing photon requirements.
- Number of events from each source related via Photon/jet ID eff. and isolation requirements.
- Model parametrised by **exponential function**.
- **Fit function to data** in CR under S+B hypothesis → count spurious signal.
- **Use simplest function with least bias** (least spurious signal events).
- Bias used as systematic.





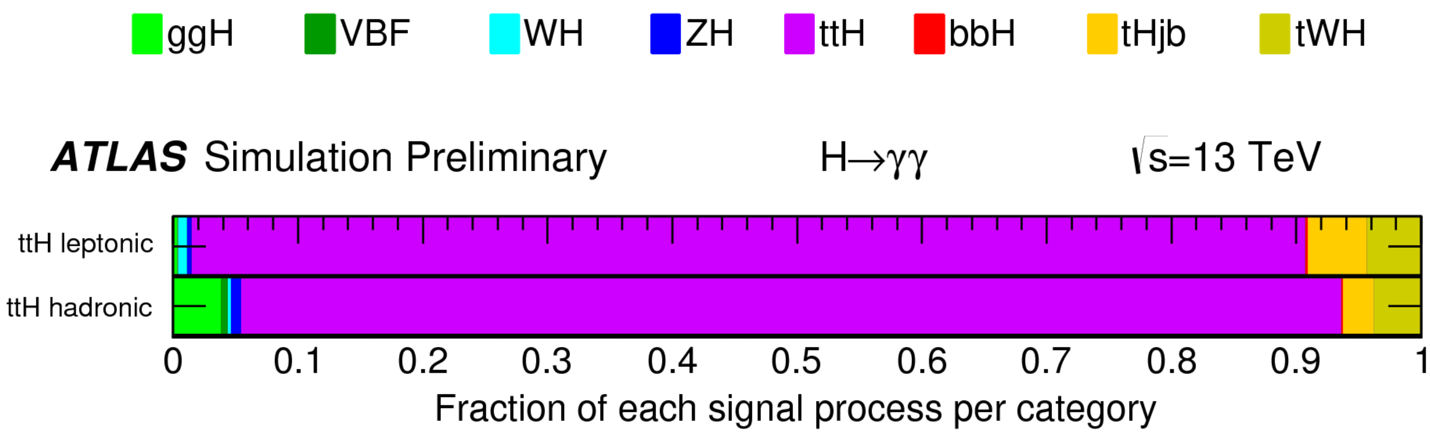
ATLAS-CONF-2016-067

ATLAS $t\bar{t}H(\gamma\gamma)$ - Selection

Control Regions

Category	Index	Photon objects	Additional objects
Hadronic	QCD::1	2 non-tight or non-isolated γs	≥ 5 jets ($p_T > 30$ GeV), ≥ 1 b-tag
	QCD::2		≥ 5 jets ($p_T > 30$ GeV)
	QCD::3		≥ 5 jets ($p_T > 25$ GeV)
Leptonic	QCD::1	2 non-tight or non-isolated γs	≥ 1 lepton, ≥ 2 jets ($p_T > 25$ GeV), ≥ 1 b-tag, $E_T^{miss} \geq 20$ GeV **or** ≥ 1 lepton, ≥ 2 jets ($p_T > 25$ GeV), ≥ 2 b-tags
	QCD::2		≥ 1 lepton, ≥ 2 jets ($p_T > 25$ GeV), $E_T^{miss} \geq 20$ GeV
	QCD::3		≥ 3 jets ($p_T > 25$ GeV), $E_T^{miss} \geq 20$ GeV

ATLAS $t\bar{t}H(\gamma\gamma)$ - Signal



CMS $t\bar{t}H(\gamma\gamma)$ - BDT

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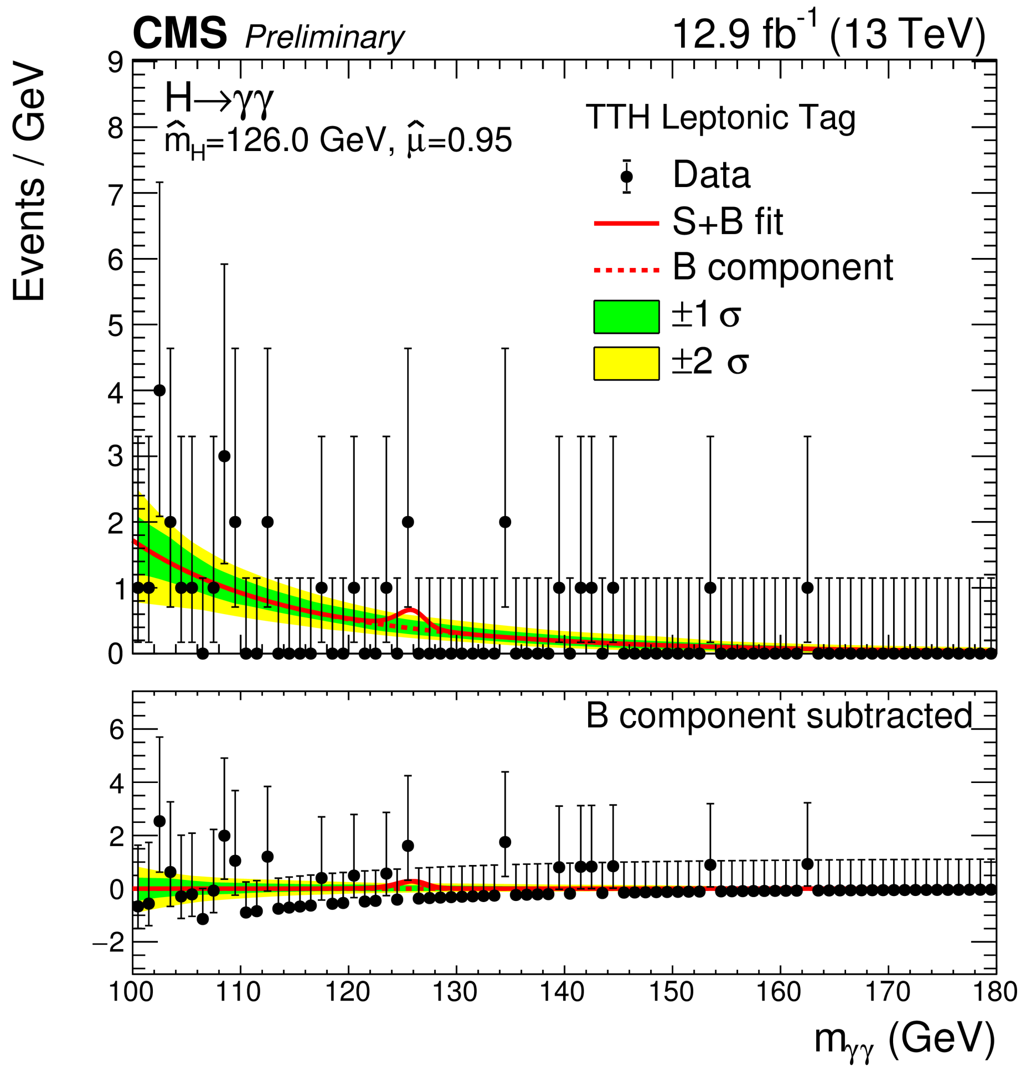
- $BDT_{\gamma\ ID}$ distinguish prompt photons from non-prompt photon background.
- For events passing pre-selection, MVA classifier trained to separate signal from background.
- $BDT_{\gamma\gamma}$ gives high score to events with signal-like kinematics, good diphoton mass resolution, photon-like values of $BDT_{\gamma\ ID}$.
- Setting requirements on this MVA allows the definition of categories with different sensitivities.
- Variable is designed to be mass independent by choosing inputs from which the mass cannot be inferred.
- The distributions of the $BDT_{\gamma\gamma}$ input variables and its output in simulation and data are compared using $Z \rightarrow ee$ events.

CMS $t\bar{t}H(\gamma\gamma)$ - Results



ATLAS $t\bar{t}H(bb)$ - Signal processes

Signal Comp.

Channel	Region	WW	$\tau\tau$	ZZ	$b\bar{b}$	$\gamma\gamma$
$H \to b\bar{b}$	ℓ+jets ($\geq$ 6j,3bj)	5%	1%	1%	90%	–
	ℓ+jets (5j,$\geq$ 4bj)	–	–	–	99%	–
	ℓ+jets ($\geq$ 6j,$\geq$ 4bj)	1%	–	1%	97%	–
	dilepton ($\geq$ 4j,3bj)	6%	1%	1%	90%	–
	dilepton ($\geq$ 4j,$\geq$ 4bj)	–	–	–	98%	–

- Target H->bb decays but accept all decays as signal.
- Dominated by H->bb with large contribution from H->WW and H->tau tau.
- Require loose lepton and tau veto to prevent overlap esp. w. multilpeton

ATLAS ttH(bb) - Signal & Background Predictions

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Process	Nominal Sample	Additional Information
tt	Powheg+Pythia6	• Categorised nominal into tt+light, tt+≥1b and tt+≥1c using hadron matching. • RW tt+light and tt+≥1c p_T(top) and p_T(tt) to NNLO prediction. • RW tt+≥1b to Sherpa OL. • tt+jets modelling uncertainty discussed later.
V+jets	Sherpa 2.1	• Use x1.3 correction factor from VH on nominal. • 30% unc. decorrelated across nJets (Z+jets in dilepton, W+jets in l+jets). • Additional 30% decorrelated across nbTags (Z+jets in dilepton, W+jets in l +jets). • 45% overall cross-section uncertainty on Z+jets in l+jets.
Single top	Powheg+Pythia6	• Diagram removal (DR) scheme
ttV	MadGraph+Pythia8	
Diboson	Sherpa 2.1	
QCD/multijet	Matrix method - l+jets Simulation - dilepton	• 2 different methods used. • Described in more detail later.
ttH	aMc@NLO+Pythia8	• M_H = 125 GeV

ATLAS ttH(bb) - ttb Uncertainties

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- New ttb systematic definitions.
- All uncertainties applied to PowPy6 Nom. with ttb RW to Sherpa OL and ttc/ttlight RW to NNLO theory predictions.

Title	**Comparison**
tt+≥1b PS and hadronisation (reweighting)	nominal ttb (5FS) reweighted to aMc@NLO+H++ (4FS) w.r.t nominal ttb (5FS) reweighted to aMc@NLO+Py8 (4FS)
tt+≥1b NLO generator (reweighting)	nominal ttb (5FS) reweighted to aMc@NLO+Py8 (4FS) w.r.t nominal ttb (5FS) reweighted to RW to Sherpa OL (4FS)
tt+≥1b radiation	Up: Pow+Py6 RadHi (5FS) RW to Sherpa OL (4FS) Down: Pow+Py6 RadLo (5FS) RW Sherpa OL (4FS)
tt+≥1b PS and hadronisation	Alternative ttb aMc@NLO+H++ AFII (5FS) w.r.t nominal ttb Pow+Py6 AFII (5FS) both reweighted to Sherpa OL (4FS)
tt+≥1b NLO generator	Alternative aMc@NLO+H++ AFII (5FS) w.r.t Pow+H++ AFII (5FS) both reweighted to SherpOL (4FS)

ATLAS ttH(bb) - NNLO RW Systematic Uncertainty

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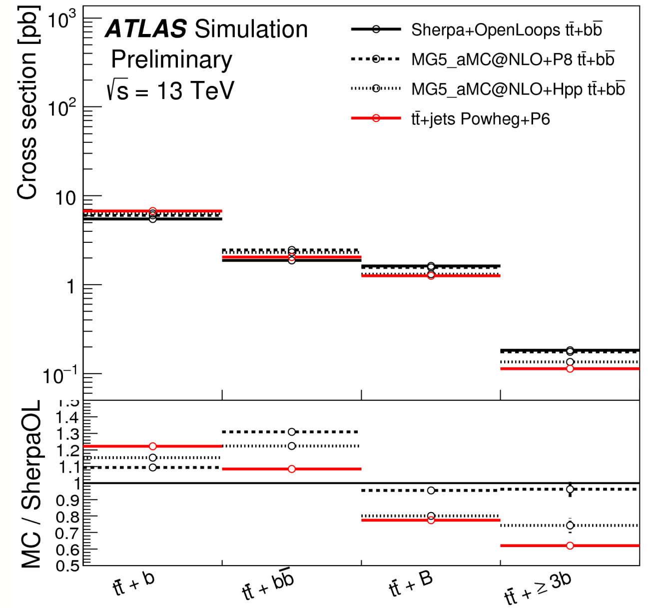
- Two associated systematics: “NNLO reweighing p_T(t)” and “NNLO reweighing p_T(tt)”.
- Compared many samples p_T(t) and p_T(tt) distributions.
- Use largest sample deviation per distribution.
- Powheg+Pythia6 RadHi for p_T(t).
- Powheg+Herwig++ for p_T(tt).
- p_T(t) Up = sequential p_T(t) Powheg+Pythia6 RW x Powheg+Pythia6 RadHi RW factor.
- p_T(tt) Up = default p_T(tt) Powheg+Pythia6 RW x Powheg+Herwig++ RW factor.

Title	Comparison
“NNLO reweighing p_T(t)”	Powheg+Pythia6 with p_T(tt) nominal RW x p_T(t) Up w.r.t nominal Powheg+Pythia6 non-RW
“NNLO reweighing p_T(tt)”	Powheg+Pythia6 with p_T(tt) Up x p_T(t) nominal sequential RW w.r.t nominal Powheg+Pythia6 non-RW

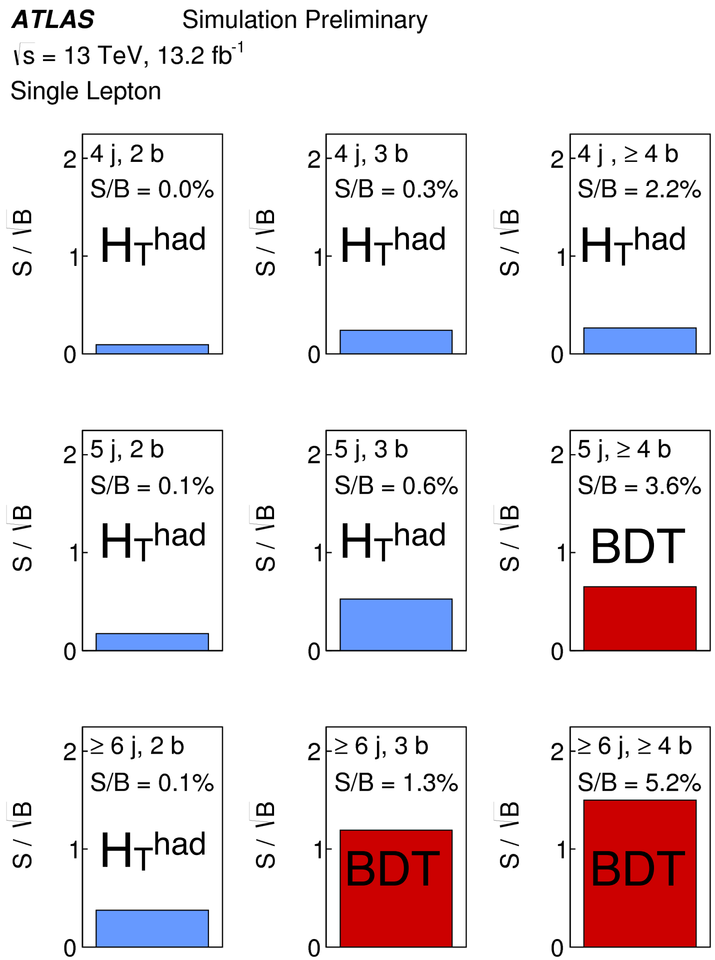
ATLAS $t\bar{t}H(bb)$ - Signal & Background

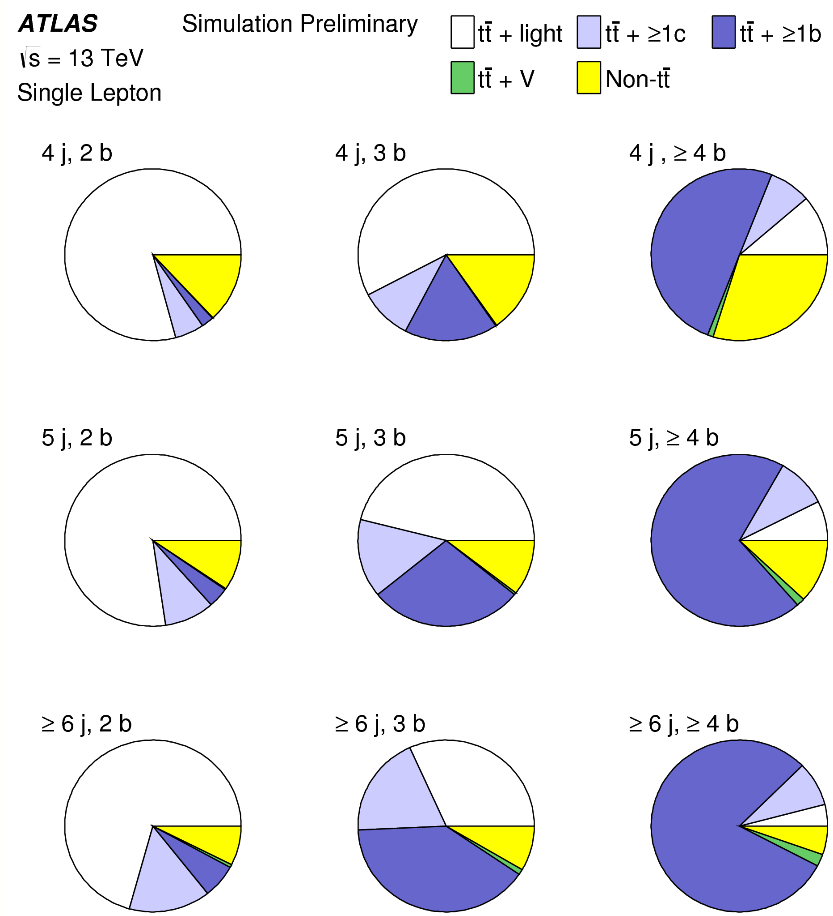
- **Same $t\bar{t}H$ signal simulation as $t\bar{t}H(\gamma\gamma)$.**
- **Dominant background = $t\bar{t}$+jets.**
- Simulated using **Powheg+Pythia6**.
- Split into 3 components: **$t\bar{t}$+light, $t\bar{t}$+≥1c and $t\bar{t}$+≥1b.**
- **$t\bar{t}$+light and $t\bar{t}$+≥1c: Correct top and $t\bar{t}$ p_T spectra to NNLO** theory prediction [Ref.].
- **$t\bar{t}$+≥1b: Correct to 4-flavour scheme NLO $t\bar{t}$+bb calculation with Sherpa+OpenLoops**.
- $t\bar{t}$+≥1b systematic uncertainty comparing with **aMC@NLO 4F $t\bar{t}$+≥1b calculation.**
- **$t\bar{t}$+≥1b and $t\bar{t}$+≥1c norm. factors free-floating in fit.**



Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.53	−0.53
Jet flavour tagging	+0.26	−0.26
$t\bar{t}H$ modelling	+0.32	−0.20
Background model statistics	+0.25	−0.25
$t\bar{t}+\geq 1c$ modelling	+0.24	−0.23
Jet energy scale and resolution	+0.19	−0.19
$t\bar{t}$+light modelling	+0.19	−0.18
Other background modelling	+0.18	−0.18
Jet-vertex association, pileup modelling	+0.12	−0.12
Luminosity	+0.12	−0.12
$t\bar{t}Z$ modelling	+0.06	−0.06
Light lepton (e, μ) ID, isolation, trigger	+0.05	−0.05
Total systematic uncertainty	+0.90	−0.75
$t\bar{t}+\geq 1b$ normalisation	+0.34	−0.34
$t\bar{t}+\geq 1c$ normalisation	+0.14	−0.14
Statistical uncertainty	+0.49	−0.49
Total uncertainty	+1.02	−0.89

ATLAS tt̄H(bb) - Analysis Regions (Single Lepton)





Channel	Region	$t\bar{t}H$ (S)	Bkgd (B)	$tHjb + WtH$	S/B	N_{Data}
	ℓ+jets ($\geq$ 6j,3bj)	119 $\pm$ 16	11250 $\pm$ 240	6.2 $\pm$ 1.5	0.011	11561
	ℓ+jets (5j,$\geq$ 4bj)	11.8 $\pm$ 2.6	429 $\pm$ 28	0.91 $\pm$ 0.14	0.028	418
$H \to b\bar{b}$	ℓ+jets ($\geq$ 6j,$\geq$ 4bj)	44.9 $\pm$ 9.4	1191 $\pm$ 55	2.10 $\pm$ 0.50	0.038	1285
	dilepton ($\geq$ 4j,3bj)	20.6 $\pm$ 4.2	1423 $\pm$ 45	0.71 $\pm$ 0.20	0.014	1467
	dilepton ($\geq$ 4j,$\geq$ 4bj)	6.6 $\pm$ 2.0	133 $\pm$ 12	0.171 $\pm$ 0.053	0.050	154

ATLAS $t\bar{t}H(bb)$ - Single Lepton BDT Inputs

Variable	Definition	Region		
		$\geq$ 6j, $\geq$ 4b	$\geq$ 6j, 3b	5j, $\geq$ 4b
General kinematic variables				
$\Delta R^{\text{avg}}_{\text{bb}}$	Average ΔR for all b-tagged jet pairs	✓	✓	✓
$\Delta R^{\text{max } p_T}_{bb}$	ΔR between the two b-tagged jets with the largest vector sum p_{T}	✓	–	–
$\Delta \eta^{\text{max}}_{\text{jj}}$	Maximum $\Delta\eta$ between any two jets	✓	✓	✓
$m^{\text{min } \Delta R}_{\text{bb}}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	✓	✓	–
$m^{\text{min } \Delta R}_{\text{jj}}$	Mass of the combination of any two jets with the smallest ΔR	–	–	✓
$m^{\text{max } p_T}_{\text{bj}}$	Mass of the combination of a b-tagged jet and any jet with the largest vector sum p_{T}	–	✓	–
$p^{\text{jet5}}_{\text{T}}$	p_{T} of the fifth leading jet	✓	✓	✓
$\text{N}^{\text{Higgs 30}}_{\text{bb}}$	Number of b-jet pairs with invariant mass within 30 GeV of the Higgs boson mass	✓	–	✓
$\text{N}^{\text{jet}}_{40}$	Number of jets with $p_{\text{T}} \geq 40 GeV$	–	✓	–
$H^{\text{had}}_{\text{T}}$	Scalar sum of jet p_{T}	–	✓	✓
$\Delta R^{\text{min } \Delta R}_{\text{lep-bb}}$	ΔR between the lepton and the combination of the two b-tagged jets with the smallest ΔR	–	–	✓
Aplanarity	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [42] built with all jets	✓	✓	✓
Centrality	Scalar sum of the p_{T} divided by sum of the E for all jets and the lepton	✓	✓	✓
$H1$	Second Fox–Wolfram moment computed using all jets and the lepton	✓	✓	✓
Variables from reconstruction BDT output				
BDT output		✓*	✓*	✓*
m_{H}	Higgs boson mass	✓	✓	✓
$m_{\text{H},b_{\text{lep top}}}$	Mass of Higgs boson and b-jet from leptonic top	✓	–	–
$\Delta R_{\text{Higgs bb}}$	ΔR between b-jets from the Higgs boson	✓	✓	✓
$\Delta R_{\text{H},t\bar{t}}$	ΔR between Higgs boson and $t\bar{t}$ system	✓*	✓*	✓*
$\Delta R_{\text{H,lep top}}$	ΔR between Higgs boson and leptonic top	✓	–	–
$\Delta R_{\text{H},b_{\text{had top}}}$	ΔR between Higgs boson and b-jet from hadronic top	–	✓*	✓*

ATLAS $t\bar{t}H(bb)$ - Dilepton BDT Inputs

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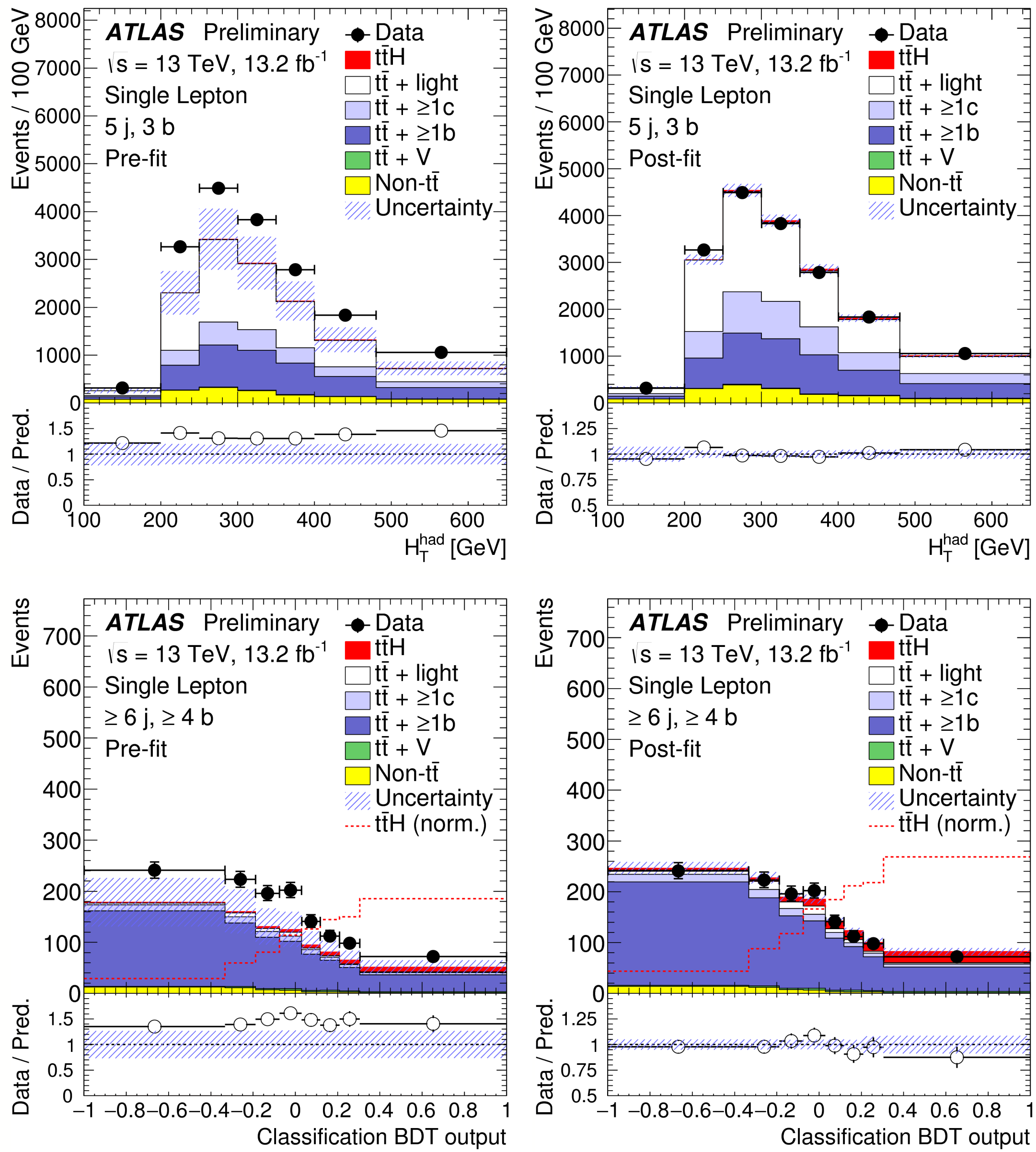
Variable	Definition	Region		
		≥ 4j, ≥ 4b	≥ 4j, 3b	3j, 3b
General kinematic variables				
$\Delta\eta_{bb}^{\mathrm{avg}}$	Average $\lvert\Delta\eta\rvert$ among pairs of b-jets	✓	–	–
$\Delta\eta_{\mathrm{bb}}^{\mathrm{max}}$	Maximum $\Delta\eta$ between any two b-jets	–	✓	✓
$\Delta\eta_{\mathrm{jj}}^{\mathrm{avg}}$	Average $\Delta\eta$ among jet pairs	–	✓	–
$\Delta R_{bb}^{\mathrm{max}\ p_T}$	ΔR between the two b-tagged jets with the largest vector sum p_{T}	✓	✓	✓
$\Delta R_{\mathrm{bb}}^{\mathrm{Higgs}}$	ΔR between the two b-tagged jets with mass closest to the Higgs boson mass	✓	–	–
$\Delta R_{\mathrm{bb}}^{\mathrm{max\ m}}$	ΔR between the two b-jets with the largest invariant mass	✓	✓	✓
$m_{\mathrm{bb}}^{\mathrm{max}\ p_T}$	Mass of the two b-tagged jets with the largest vector sum p_{T}	–	–	✓
$m_{\mathrm{bb}}^{\mathrm{Higgs}}$	Mass of the two b-tagged jets closest to the Higgs boson mass	✓	✓	✓
$m_{\mathrm{bb}}^{\mathrm{min}}$	Minimum mass of two b-tagged jets	–	–	✓
$m_{\mathrm{bb}}^{\mathrm{min}\ \Delta R}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	✓	✓	✓
$p_{\mathrm{T},b}^{\mathrm{min}}$	Minimum b-tagged jet p_{T}	–	–	✓
$H_{\mathrm{T}}^{\mathrm{all}}$	Scalar p_{T} sum of all leptons and jets	–	✓	✓
$\mathrm{N}_{\mathrm{bb}}^{\mathrm{Higgs\ 30}}$	Number of b-jet pairs with invariant mass within 30 GeV of the Higgs boson mass	✓	–	✓
$\mathrm{N}_{\mathrm{jj}}^{\mathrm{Higgs\ 30}}$	Number of jet pairs with invariant mass within 30 GeV of the Higgs boson mass	–	✓	–
Aplanarity	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [42] built with all jets	✓	✓	✓
Centrality	Sum of the p_{T} divided by sum of the E for all jets and both leptons	✓	–	✓
$H2_{\mathrm{jets}}$	Third Fox–Wolfram moment computed using all jets	–	✓	–
$H4_{\mathrm{all}}$	Fifth Fox–Wolfram moment computed using all jets and leptons	–	–	✓
Variables from reconstruction BDT output				
BDT output		✓*	✓*	–
m_{H}	Higgs boson mass	✓(*)	✓(*)	–
$\Delta\eta_{\mathrm{H},l}^{\mathrm{min}}$	Minimum $\Delta\eta$ between the Higgs boson and a lepton	✓*	✓	–
$\Delta\eta_{\mathrm{H},l}^{\mathrm{max}}$	Maximum $\Delta\eta$ between the Higgs boson and a lepton	✓*	✓	–
$\Delta\eta_{\mathrm{H,b}}^{\mathrm{min}}$	Minimum $\Delta\eta$ between the Higgs boson and a b-jet	✓*	–	–

ATLAS tt̄H(bb) - Analysis Strategy

- **Fit discriminant distributions.**
- Two MVAs used in signal regions:
    - **Reco. BDT**: Associate jets to Higgs or top quarks.
    - **Classif. BDT**: Separate background and signal.



ATLAS $t\bar{t}H(bb)$ - Systematics

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.53	−0.53
Jet flavour tagging	+0.26	−0.26
$t\bar{t}H$ modelling	+0.32	−0.20
Background model statistics	+0.25	−0.25
$t\bar{t}+\geq 1c$ modelling	+0.24	−0.23
Jet energy scale and resolution	+0.19	−0.19
$t\bar{t}$+light modelling	+0.19	−0.18
Other background modelling	+0.18	−0.18
Jet-vertex association, pileup modelling	+0.12	−0.12
Luminosity	+0.12	−0.12
$t\bar{t}Z$ modelling	+0.06	−0.06
Light lepton (e, μ) ID, isolation, trigger	+0.05	−0.05
Total systematic uncertainty	+0.90	−0.75
$t\bar{t}+\geq 1b$ normalisation	+0.34	−0.34
$t\bar{t}+\geq 1c$ normalisation	+0.14	−0.14
Statistical uncertainty	+0.49	−0.49
Total uncertainty	+1.02	−0.89

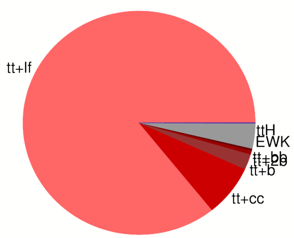
Summary of the post-fit impact of the systematic uncertainties on μ. The background model statistics refers to the statistical uncertainties from the limited number of simulated events and from the data-driven determination of the non-prompt and fake lepton background component in the single-lepton channel. Due to correlations between the different sources of uncertainties, the total systematic uncertainty can be different from the sum in quadrature of the individual sources. This leads to an asymmetry in the total uncertainty which is not present in the individual sources. The normalisation factors for both tt+≥ 1b and tt +≥ 1c are included in the statistical component.

CMS PAS HIG-16-004

Dilepton

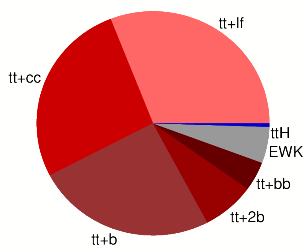
CMS *Simulation*

3 jets, 2 b-tags



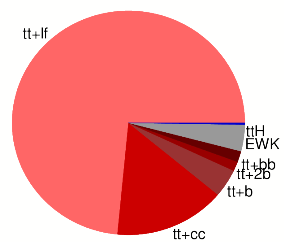
S/B=0.000, S/√B=0.026

3 jets, 3 b-tags



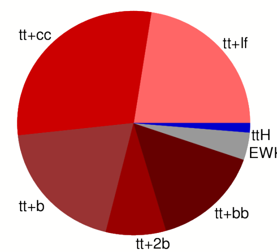
S/B=0.005, S/√B=0.047

≥ 4 jets, 2 b-tags



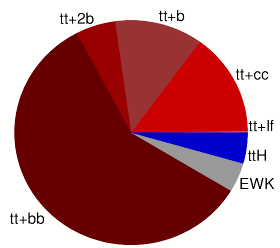
S/B=0.003, S/√B=0.148

≥ 4 jets, 3 b-tags

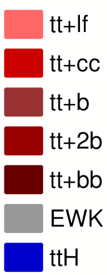


S/B=0.014, S/√B=0.223

≥ 4 jets, ≥ 4 b-tags



S/B=0.046, S/√B=0.221



	3 jets, 2 b-tags	3 jets, 3 b-tags	≥ 4 jets, 2 b-tags	≥ 4 jets, 3 b-tags	≥ 4 jets, ≥ 4 b-tags
$t\bar{t}$+lf	2558.6 ± 542.7	26.6 ± 10.5	2271.6 ± 505.0	60.3 ± 25.6	0.9 ± 0.8
$t\bar{t} + c\bar{c}$	220.9 ± 103.4	22.7 ± 13.6	478.4 ± 234.4	78.4 ± 45.4	3.4 ± 2.9
$t\bar{t}$+b	65.4 ± 28.5	21.4 ± 10.2	126.2 ± 57.7	52.2 ± 25.1	2.7 ± 1.6
$t\bar{t}$+2b	16.9 ± 7.6	6.6 ± 3.1	42.9 ± 20.2	22.3 ± 10.7	1.2 ± 0.7
$t\bar{t} + b\bar{b}$	8.6 ± 4.2	3.6 ± 1.8	48.9 ± 23.7	39.8 ± 18.8	13.4 ± 7.1
Single Top	93.2 ± 16.7	3.0 ± 1.0	87.6 ± 15.8	7.3 ± 2.5	0.4 ± 0.4
V+jets	14.5 ± 11.0	1.3 ± 0.8	16.0 ± 7.4	0.0 ± 0.0	0.0 ± 0.0
$t\bar{t}$+V	3.6 ± 0.9	0.3 ± 0.2	16.4 ± 3.2	3.2 ± 0.9	0.5 ± 0.2
Diboson	1.7 ± 0.9	0.0 ± 0.0	1.2 ± 1.0	0.1 ± 0.0	0.0 ± 0.0
Total bkg	2983.4 ± 590.4	85.6 ± 25.6	3089.2 ± 650.6	263.6 ± 79.9	22.5 ± 9.8
$t\bar{t}$H	1.4 ± 0.2	0.4 ± 0.1	8.1 ± 1.1	3.6 ± 0.6	1.0 ± 0.3
Data	3123	115	2943	319	27
S/B	0.00047	0.0051	0.0026	0.014	0.046
Data/B	1.0 ± 0.2	1.3 ± 0.4	1.0 ± 0.2	1.2 ± 0.3	1.2 ± 0.5

CMS $t\bar{t}H(bb)$ - Analysis Regions (Single lepton)

Process	$\geq$ 6 jets, 2 b-tags	4 jets, 3 b-tags	5 jets, 3 b-tags	$\geq$ 6 jets, 3 b-tags
$t\bar{t}$+lf	5359.3 ± 1226.3	2026.1 ± 651.4	1000.2 ± 352.9	589.5 ± 199.7
$t\bar{t}+c\bar{c}$	1722.2 ± 849.5	363.2 ± 190.9	368.1 ± 191.3	396.6 ± 209.5
$t\bar{t}$+b	393.7 ± 188.2	203.1 ± 92.5	199.6 ± 90.8	170.8 ± 81.4
$t\bar{t}$+2b	165.2 ± 81.2	78.9 ± 38.0	87.2 ± 40.7	97.3 ± 46.8
$t\bar{t}+b\bar{b}$	226.4 ± 113.2	75.8 ± 35.3	114.1 ± 52.3	183.7 ± 86.7
Single Top	283.0 ± 49.0	115.3 ± 30.8	76.2 ± 19.5	47.5 ± 12.7
V+jets	130.5 ± 35.2	38.6 ± 17.8	22.8 ± 10.4	13.6 ± 6.4
$t\bar{t}$+V	43.5 ± 8.2	4.3 ± 1.2	6.4 ± 1.8	10.0 ± 2.7
Diboson	2.8 ± 1.3	2.1 ± 1.3	0.9 ± 0.5	0.2 ± 0.3
Total bkg	8326.7 ± 1788.6	2907.4 ± 836.5	1875.5 ± 534.7	1509.1 ± 423.7
$t\bar{t}$H	29.6 ± 2.1	7.4 ± 1.0	10.9 ± 1.2	16.7 ± 2.1
Data	7185	2793	1914	1386
S/B	0.0036	0.0026	0.0059	0.011
Data/B	0.9 ± 0.2	1.0 ± 0.3	1.0 ± 0.3	0.9 ± 0.3

Process	4 jets, $\geq$ 4 b-tags	5 jets, $\geq$ 4 b-tags	$\geq$ 6 jets, $\geq$ 4 b-tags	boosted
$t\bar{t}$+lf	17.8 ± 10.8	17.7 ± 10.9	17.6 ± 11.3	45.1 ± 9.4
$t\bar{t}+c\bar{c}$	11.6 ± 8.2	22.1 ± 15.4	35.9 ± 24.9	21.8 ± 12.0
$t\bar{t}$+b	8.4 ± 4.4	14.8 ± 7.7	20.0 ± 10.9	10.3 ± 5.5
$t\bar{t}$+2b	3.5 ± 1.9	6.9 ± 3.7	12.3 ± 6.9	12.3 ± 6.6
$t\bar{t}+b\bar{b}$	10.1 ± 4.9	28.8 ± 13.9	73.4 ± 36.6	17.0 ± 8.4
Single Top	2.5 ± 1.1	4.3 ± 1.4	5.5 ± 2.0	7.0 ± 1.7
V+jets	1.0 ± 0.8	0.9 ± 0.8	1.4 ± 0.7	2.5 ± 0.8
$t\bar{t}$+V	0.3 ± 0.1	0.7 ± 0.3	1.6 ± 0.6	0.9 ± 0.3
Diboson	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.1
Total bkg	55.2 ± 23.0	96.5 ± 37.6	167.6 ± 65.7	117.0 ± 24.9
$t\bar{t}$H	0.9 ± 0.2	2.7 ± 0.6	5.9 ± 1.4	2.2 ± 0.3
Data	75	104	150	104
S/B	0.017	0.028	0.035	0.019
Data/B	1.4 ± 0.5	1.1 ± 0.4	0.9 ± 0.4	0.9 ± 0.2

CMS $t\bar{t}H(bb)$ - Analysis Strategy

CMS PAS HIG-16-004

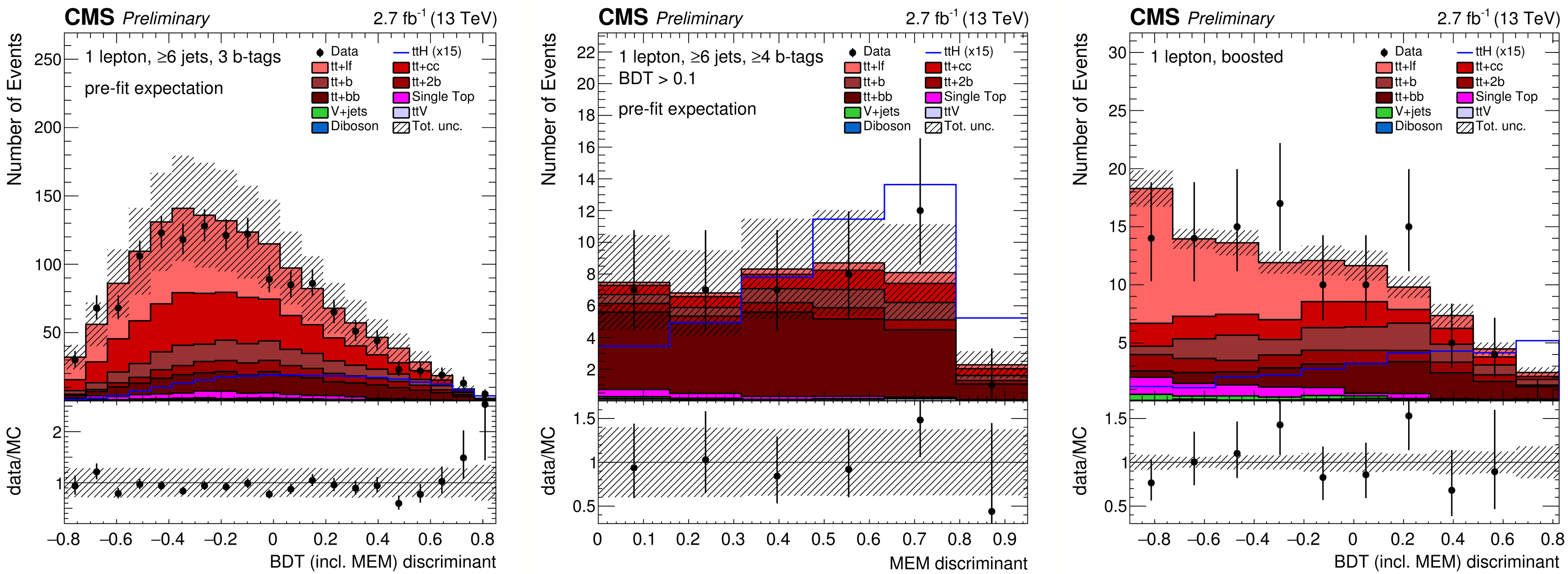
- **BDT and Matrix Element Method** (MEM) used to improve signal discrimination.
- **Separate BDT trained in each region** ($t\bar{t}H$ v $t\bar{t}$+jets).
- Matrix element method (MEM) determines **probability an observed event is consistent with a particular hypothesis**.

2 and 3 b-tag regions

- **BDT final discriminant (includes MEM** as input variable in the 3 b-tags categories).

≥4 b-tag regions

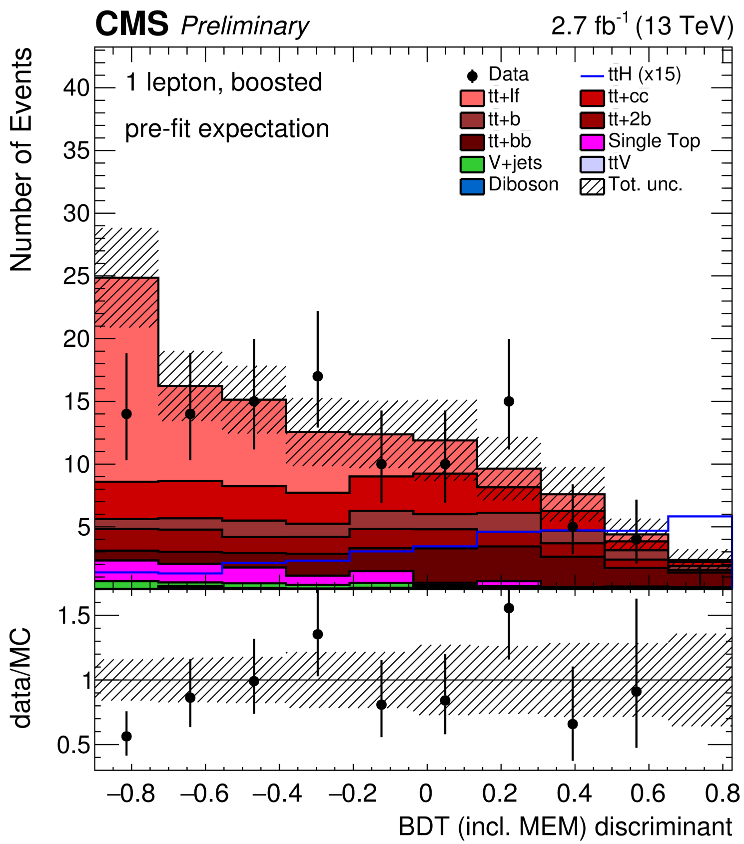
- **2 categories**: one **low** and one **high BDT output** (according to median of distribution).
- **MEM as final discriminant** (better at discriminating against $t\bar{t}$+bb).

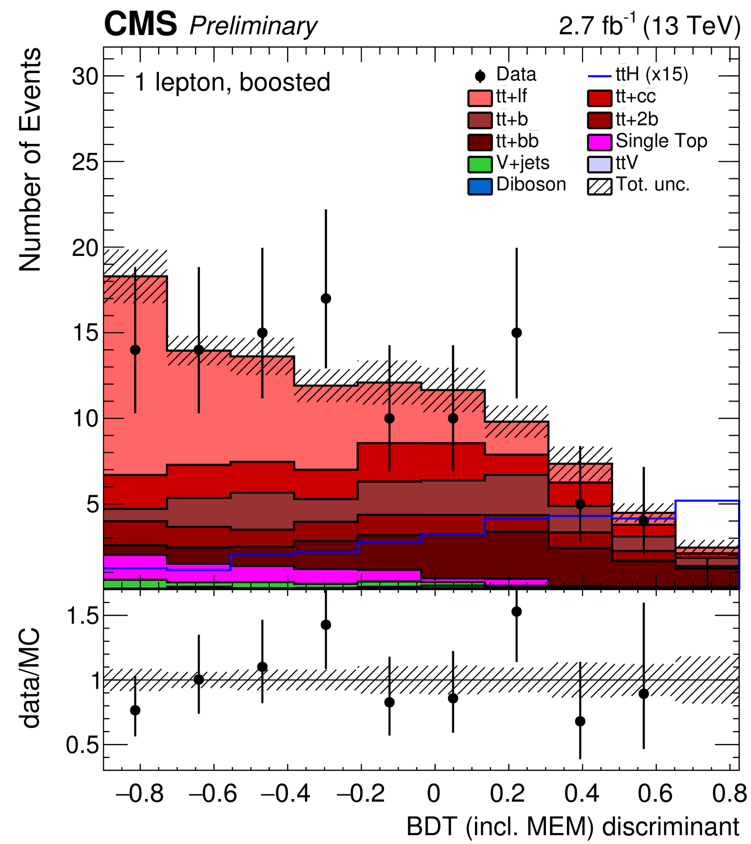


CMS $t\bar{t}H(bb)$ - Boosted Category

CMS PAS HIG-16-004

- **Require reconstructed boosted hadronic top and Higgs candidate**
- **Reduced combinatorial background when assigning jets to Higgs and top quarks increases the sensitivity of region.**
- Discriminant distribution: **BDT using MEM** as one of several inputs.
- MEM output is particularly powerful **discrimination variable**.





CMS ttH(bb) - MEM

- Matrix element method (MEM) determines probability an observed event is consistent with a particular hypothesis.
- Each event is assigned a probability density value computed from the four-momenta of the reconstructed particles, which is based on the differential cross section of the signal or background process.
- MEM discriminant is constructed as ratio of the probability density values of the signal and background hypothesis.
- Test both hypotheses and create discriminating variable using likelihood ratio.
- The probability density functions are constructed at LO, assuming gluon-gluon fusion production both for signal and background processes.
- In the 2 and 3 b-tag categories: BDT final discriminant which includes MEM as input variable (in the three b-tags categories). These categories contain a relatively large number of events, which is favourable for training the BDT.

CMS ttH(bb) - BDT Inputs Single Lepton

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Event variable	Description
Object and event kinematics	
jet 1, 2, 3, 4 p_T	Jet transverse momenta, jets ordered in p_T
HT	Scalar sum of transverse momentum for all jets with $p_T > 30$ GeV/c
MET	Missing transverse energy
$\sum p_T$(jets,leptons,MET)	Sum of the p_T of all jets, leptons, and MET
mass(lepton,jet,MET)	Invariant mass of the 4-vector sum of all jets, leptons, and MET
avg ΔR(tag,tag)	Average ΔR between b-tagged jets
avg $\Delta\eta$(jet,jet)	Average $\Delta\eta$ between jets
max $\Delta\|\eta\|$ (jet, avg jet $\|\eta\|$)	max difference between jet $\|\eta\|$ and avg $\|\eta\|$ of jets
max $\Delta\|\eta\|$ (tag, avg jet $\|\eta\|$)	max difference between tag $\|\eta\|$ and avg $\|\eta\|$ of jets
max $\Delta\|\eta\|$ (tag, avg tag $\|\eta\|$)	max difference between tag $\|\eta\|$ and avg η of tags
min ΔR(tag,tag)	ΔR between the two closest b-tagged jets
M3	Invariant mass of the 3-jet system with largest transverse momentum
min ΔR(lepton,jet)	ΔR between the lepton and the closest jet (LJ channel)
mass(lepton,closest tag)	Invariant mass of the lepton and the closest b-tagged jet in ΔR (LJ channel)
closest tagged dijet mass	Invariant mass of the two b-tagged jets that are closest in ΔR
tagged dijet mass closest to 125	Invariant mass of the b-tagged pair closest to 125 GeV/c^2
best Higgs mass	A minimum-chi-squared fit to event kinematics is used to select two b-tagged jets as top-decay products. Of the remaining b-tagged jets, the invariant mass of the two with highest E_T is saved.
$\sqrt{\Delta\eta(t^{lep},bb)\times\Delta\eta(t^{had},bb)}$	Square root of the product of abs $\Delta\eta$ (leptonic top, bb) and abs $\Delta\eta$ (hadronic top, bb), where the bb-system and the candidates for the leptonic and hadronic tops are found with the best higgs mass algorithm
$(\Sigma$ jet $p_T)/(\Sigma$ jet E)	Ratio of the sum of the transverse momentum of all jets and the sum of the energy of all jets
CSVv2IVF b-tag	
first- to fifth-highest CSV	First- to fifth-highest highest CSVv2IVF discriminator value of all jets
avg CSV (tags/all)	Average b-tag discriminator value for b-tagged/all jets
dev from avg CSV (tags)	Squared difference between the CSVv2IVF discriminator value of a given b-tagged jet and the average CSVv2IVF discriminator value among b-tagged jets, summed over all b-tagged jets
sphericity	Sphericity: $3/2(\lambda_2+\lambda_3)$ (λ_i: eigenvalues of momentum tensor)
aplanarity	Aplanarity: $3/2\lambda_1$ (λ_i: eigenvalues of momentum tensor)
H_1, H_2, H_3, H_4	Fox-Wolfram moments [74]

CMS ttH(bb) - BDT Inputs Single Lepton

Event variable	Description
MEM discriminator	
MEM discriminator	MEM discriminator
Boosted object and event reconstruction	
τ_2/τ_1 Higgs cand.	2-subjettiness to 1-subjettiness ratio of Higgs candidate fat jet [75]
m(Higgs, di-filterjet)	Invariant mass of boosted Higgs candidate reconstructed from filtered subjets B1 and B2
$\Delta\eta$(top,Higgs)	Pseudo rapidity difference between boosted top candidate and boosted Higgs candidate
MEM discriminator (using subjets)	MEM discriminator using the subjets from the boosted top candidate

CMS ttH(bb) - BDT Inputs Single Lepton

≥ 4 jets, ≥ 2 b-tags boosted	4 jets, 3 b-tags	4 jets, ≥ 4 b-tags
avg ΔR(tag,tag) τ_2/τ_1 of Higgs cand. third-highest CSV fourth-highest CSV $\Delta\eta$(top,Higgs) aplanarity m(Higgs, di-filterjet) min ΔR(tag,tag) avg CSV (all) MEM discriminator (using subjets) b-tagging likelihood ratio	H_1 b-tagging likelihood ratio $\sum p_T$(jets,leptons,MET) MEM discriminator avg CSV (tags) avg CSV (all) jet 2 p_T jet 4 p_T	closest tagged dijet mass b-tagging likelihood ratio $\sum p_T$(jets,lepton,MET) avg ΔR(tag,tag) H_3 jet 1 p_T
	5 jets, 3 b-tags	5 jets, ≥ 4 b-tags
	MEM discriminator avg ΔR(tag,tag) min ΔR(lepton,jet) b-tagging likelihood ratio fourth-highest CSV H_1 dev from avg CSV (tags) avg $\Delta\eta$(jet,jet) avg CSV (tags) avg CSV (all) max $\Delta\|\eta\|$ (tag, avg jet $\|\eta\|$)	b-tagging likelihood ratio jet 3 p_T tagged dijet mass closest to 125 avg $\Delta\eta$(jet,jet) avg ΔR(tag,tag) H_1 fifth-highest CSV (Σ jet p_T)/(Σ jet E)
≥ 6 jets, 2 b-tags	≥ 6 jets, 3 b-tags	≥ 6 jets, ≥ 4 b-tags
avg $\Delta\eta$(tag,tag) avg ΔR(tag,tag) ΔR(jet1, jet2) b-tagging likelihood ratio max $\Delta\|\eta\|$ (tag, avg tags $\|\eta\|$) third-highest CSV sphericity fourth-highest CSV max $\Delta\|\eta\|$ (tag, avg jet $\|\eta\|$) min ΔR(tag,tag)	b-tagging likelihood ratio $\sqrt{\Delta\eta(t^{lep}, bb) \times \Delta\eta(t^{had}, bb)}$ HT MEM discriminator $\sum p_T$(jets,lepton,MET) H_1 fourth-highest CSV avg CSV (tags) max $\Delta\|\eta\|$ (tag, avg jet $\|\eta\|$)	$\sum p_T$(jets,leptons,MET) H_3 best Higgs mass b-tagging likelihood ratio tagged dijet mass closest to 125 fifth-highest CSV (Σ jet p_T)/(Σ jet E) jet 4 p_T sphericity max $\Delta\|\eta\|$ (tag, avg tag $\|\eta\|$) second-highest CSV

CMS ttH(bb) - BDT Inputs Dilepton

Event variable	Description
Object and event kinematics	
$\langle \Delta R_{tag,tag} \rangle$	Average ΔR between b-tagged jets
$\sum p_{T\,jets,leptons}$	Sum of the p_T of all jets and leptons
$\tau^{\text{max mass}}_{jet,jet}$	Twist angle between jet pair
$\min \Delta R_{tag,tag}$	ΔR between the two closest b-tagged jets
$\max \Delta\eta_{tag,tag}$	$\Delta\eta$ between the two furthest b-tagged jets
$m^{min\Delta R}_{jet,jet}$	Invariant mass of jet pair ΔR
$M^{jj}_{higgs-like}$	Invariant mass of a jet pair ordered in closeness to a Higgs mass
$m^{min\ \Delta R}_{tag,tag}$	Invariant mass of b-tag jet pair with minimum ΔR
$p^{min\ \Delta R}_{T\ tag,tag}$	Sum p_T of b-tag jet pair with minimum ΔR
Centrality (tags)	Ratio of the sum of the transverse momentum of all b-tagged jets and the sum of the energy of all b-tagged jets
H_T	Scalar sum of transverse momentum for all jets
$\min \Delta R_{jet,jet}$	ΔR between the two closest jets
median $\mathrm{m}_{jet,jet}$	Median invariant mass of all combinations of jet pairs
$\mathrm{m}^{\text{max mass}}_{\text{tag,tag}}$	Invariant mass of b-tagged jet pair with maximum invariant mass combination
$\langle \Delta R_{jet,tag} \rangle$	Average ΔR between jets (with at least one b-tagged)
$p^{min\ \Delta R}_{T\ jet,tag}$	Sum p_T of jet pair with minimum ΔR between them (with at least one b-tag jet)
$\tau^{\text{max mass}}_{jet,tag}$	Twist angle between jet pair (with at least one b-tagged)
$\mathrm{m}^{\text{max } p_T}_{\text{jet,tag,tag}}$	Invariant mass of the 3-jet system with the largest transverse momentum where at least two jets are *b*-tagged.
$M^{bj}_{higgs-like}$	Invariant mass of a jet pair (with at least one b-tagged) ordered in closeness to a Higgs mass.
CSVv2IVF b-tag	
$\langle d \rangle_{tagged/untagged}$	Average CSV b-tag discriminant value for b-tagged/un-b-tagged jets
Event shape	
H_0, H_1, H_2, H_3, H_4	Fox-Wolfram moments [74]

CMS ttH(bb) - BDT Inputs Dilepton

3 jets, 2 b-tags	3 jets, 3 b-tags	$\geq$ 4 jets, 2 b-tags	$\geq$ 4 jets, 3 b-tags	$\geq$ 4 jets, $\geq$ 4 b-tags
$\langle d \rangle_{untagged}$	$\langle d \rangle_{tagged}$	median $\mathrm{m}_{jet,jet}$	min $\Delta R_{tag,tag}$	min $\Delta R_{tag,tag}$
$\sum p_{T\,jets,leptons}$	$m^{min\Delta R}_{tag,tag}$	$\mathrm{H}_1/\mathrm{H}_0(\mathrm{tags})$	$\langle d \rangle_{untagged}$	median $\mathrm{m}_{jet,jet}$
$\tau^{\mathrm{max\ mass}}_{jet,jet}$	$\mathrm{m}^{\mathrm{max\ mass}}_{\mathrm{tag,tag}}$	$m^{min\Delta R}_{jet,jet}$	$\langle d \rangle_{tagged}$	max $\Delta\eta_{tag,tag}$
min $\Delta R_{tag,tag}$	max $\Delta\eta_{jet,jet}$	$\langle d \rangle_{untagged}$	$m^{min\Delta R}_{tag,tag}$	$M^{jj}_{higgs-like}$
max $\Delta\eta_{tag,tag}$	$\mathrm{H}_4/\mathrm{H}_0(\mathrm{tags})$	$\mathrm{H}_2(jets)$	$M^{jj}_{higgs-like}$	H^{tags}_{T}
$m^{min\Delta R}_{jet,jet}$	$\mathrm{H}_1(jets)$	$\sum p_{T\,jets,leptons}$	max $\Delta\eta_{tag,tag}$	$\langle d \rangle_{tagged}$
$M^{jj}_{higgs-like}$	$\tau^{\mathrm{max\ mass}}_{jet,jet}$	$\langle \Delta R_{jet,tag} \rangle$	$\langle \Delta R_{jet,tag} \rangle$	$m^{min\Delta R}_{jet,tag}$
$m^{min\Delta R}_{tag,tag}$	$\sum p_{T\,jets,leptons}$	H^{jets}_{T}	$\mathrm{H}_2(tags)$	$m^{min\Delta R}_{jet,jet}$
	min $\Delta R_{jet,jet}$	$m^{min\Delta R}_{tag,tag}$	$\sum p_{T\,jets,leptons}$	$\mathrm{m}^{\mathrm{max\ mass}}_{\mathrm{tag,tag}}$
	$M^{bj}_{higgs-like}$	$p^{min\,\Delta R}_{T\ jet,tag}$	$\tau^{\mathrm{max\ mass}}_{tag,tag}$	max $\Delta\eta_{jet,jet}$
			Centrality(jets & leptons)	Centrality(jets & leptons)
			$\mathrm{m}^{\mathrm{max}\ p_T}_{\mathrm{jet,jet,jet}}$	Centrality(tags)

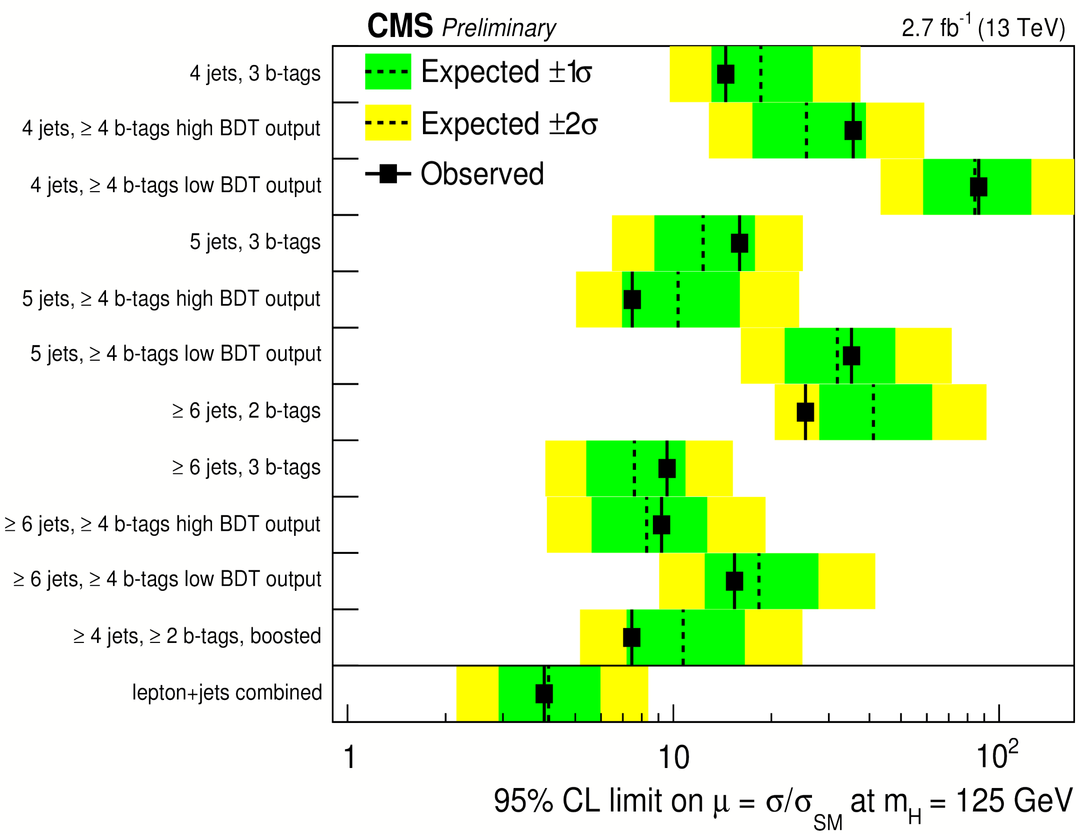
CMS $t\bar{t}H(bb)$ - 8 TeV Results

CMS-PAS-HIG-13-019

8 TeV

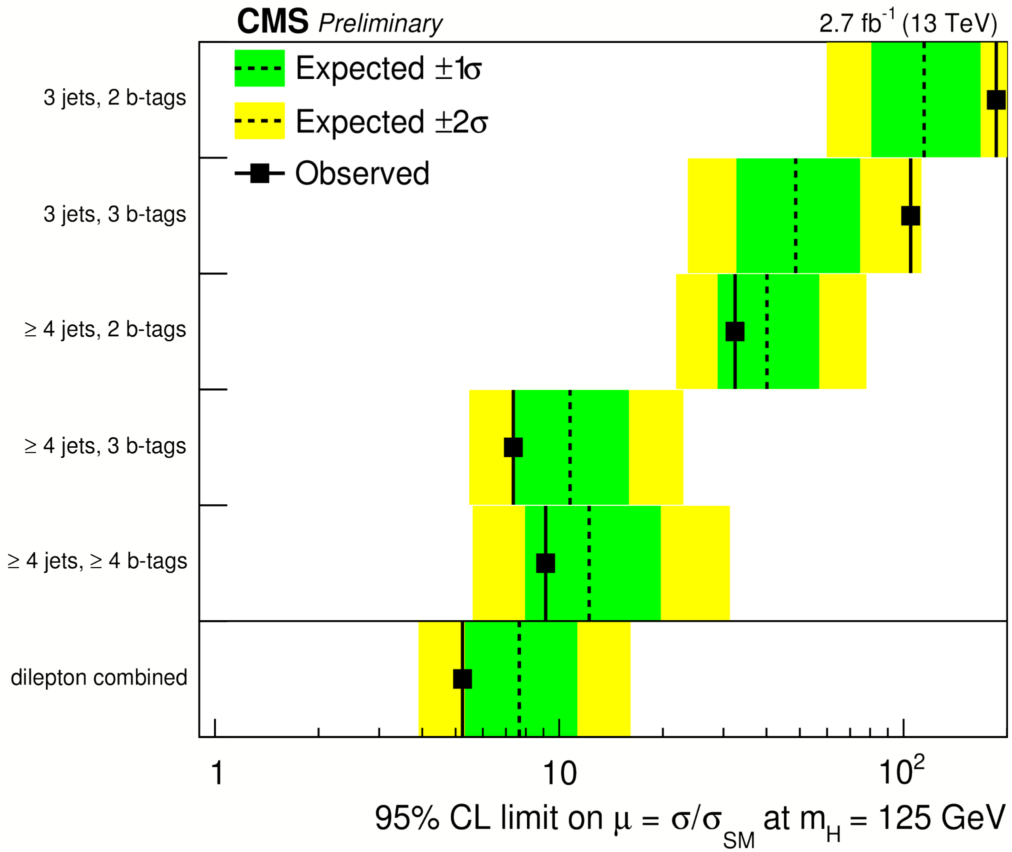
$H \to b\bar{b}$ Channel	Best fit (68% CL) Observed	Upper limits (95% CL) Observed	Upper limits (95% CL) Expected	Signal significance Observed	Signal significance Expected
VH	0.89 ± 0.43	1.68	0.85	2.08	2.52
$t\bar{t}H$	0.7 ± 1.8	4.1	3.5	0.37	0.58
VBF	$2.8^{+1.6}_{-1.4}$	5.5	2.5	2.20	0.83
Combined	$1.03^{+0.44}_{-0.42}$	1.77	0.78	2.56	2.70

CMS ttH(bb) - Results Single Lepton Regions



Category	Observed	Expected
4 jets, 3 b-tags	14.5	$18.6^{+8.2}_{-5.5}$
4 jets, ≥ 4 b-tags high BDT output	35.7	$25.6^{+13.4}_{-8.1}$
4 jets, ≥ 4 b-tags low BDT output	86.6	$84.2^{+41.3}_{-25.8}$
5 jets, 3 b-tags	16.0	$12.3^{+5.5}_{-3.6}$
5 jets, ≥ 4 b-tags high BDT output	7.5	$10.3^{+5.6}_{-3.4}$
5 jets, ≥ 4 b-tags low BDT output	35.2	$31.9^{+16.1}_{-9.9}$
≥ 6 jets, 2 b-tags	25.4	$41.1^{+21.1}_{-13.1}$
≥ 6 jets, 3 b-tags	9.6	$7.6^{+3.3}_{-2.2}$
≥ 6 jets, ≥ 4 b-tags high BDT output	9.2	$8.3^{+4.4}_{-2.7}$
≥ 6 jets, ≥ 4 b-tags low BDT output	15.4	$18.3^{+9.6}_{-5.8}$
≥ 4 jets, ≥ 2 b-tags, boosted	7.5	$10.7^{+5.9}_{-3.5}$
lepton+jets combined	4.0	$4.1^{+1.8}_{-1.2}$

CMS ttH(bb) - Results Dilepton Regions



Category	Observed	Expected
3 jets, 2 b-tags	186.0	$114.8^{+52.6}_{-34.1}$
$\geq$ 3 jets, 3 b-tags	104.9	$48.6^{+26.2}_{-15.9}$
$\geq$ 4 jets, 2 b-tags	32.4	$40.1^{+16.8}_{-11.3}$
$\geq$ 4 jets, 3 b-tags	7.4	$10.8^{+5.2}_{-3.3}$
$\geq$ 4 jets, $\geq$ 4 b-tags	9.1	$12.2^{+7.5}_{-4.3}$
dilepton combined	5.2	$7.7^{+3.6}_{-2.3}$

ATLAS $t\bar{t}H(WW^{(*)},ZZ^{(*)},\tau\tau)$ - Region Contributions

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Category	Higgs boson decay mode WW^*	$\tau\tau$	ZZ^*	Other	$A \times \epsilon$ $(\times 10^{-4})$
$2\ell 0\tau_{\text{had}}$	77%	17%	3%	3%	14
$2\ell 1\tau_{\text{had}}$	46%	51%	2%	1%	2.2
3ℓ	74%	20%	4%	2%	9.2
4ℓ	72%	18%	9%	2%	0.88

Fraction of the expected ttH signal arising from different Higgs boson decay modes in each analysis category and acceptance times efficiency (A×ε) for ttH signal in each category. The decays contributing to the ``other" column are dominantly H→μμ and H→bb. Rows may not add to 100% due to rounding. The acceptance times efficiency includes Higgs boson and top quark branching fractions, detector acceptance, and reconstruction and selection efficiency, and is computed relative to inclusive ttH production.

ATLAS $t\bar{t}H(WW^{(*)},ZZ^{(*)},\tau\tau)$ - Region Composition

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Channel	Region	$t\bar{t}H$ (S)	Bkgd (B)	$tHjb + WtH$	S/B	N_{Data}
$H \to (WW, \tau\tau, ZZ)$	$2\ell SS\ ee$	1.99 ± 0.51	22.2 ± 3.4	0.10 ± 0.03	0.09	26
	$2\ell SS\ e\mu$	4.82 ± 0.95	38.5 ± 5.1	0.26 ± 0.07	0.13	59
	$2\ell SS\ \mu\mu$	2.85 ± 0.58	21.2 ± 3.8	0.15 ± 0.04	0.13	31
	$2\ell SS + \tau_{had}$	1.43 ± 0.31	5.7 ± 1.7	0.11 ± 0.03	0.25	14
	3ℓ	6.2 ± 1.1	38.9 ± 5.3	0.30 ± 0.08	0.16	46
	4ℓ	0.59 ± 0.10	1.42 ± 0.24	0.014 ± 0.006	0.42	0

Expected signal yields (S) and background yields (B) in each ttH search analysis. Only the most sensitive signal regions are shown for ttH (H→bb). The tHjb and WtH yields after the combined fit are shown for each signal region, and are included in the background yields. The uncertainties include both statistical and systematic components. For H→(ww,ZZ,$\tau\tau$), H→bb and H→$\gamma\gamma$ analyses, the yields correspond to 13.2 (13.3) fb-1 of collision data at √s = 13 TeV. In the case of the H→$\gamma\gamma$ the effect of background is illustrated by providing the number off background events after the fit to data in the smallest diphoton mass interval expected to contain 90% of the SM signal events. This corresponds to a diphoton mass interval of [121.9-127.8] GeV and [121.9-127.9] GeV in the leptonic and hadronic channels respectively.

ATLAS $t\bar{t}H(WW^{(*)}, ZZ^{(*)}, \tau\tau)$ - Region Contribution

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ATLAS-CONF-2016-058

	$2\ell 0\tau_{\rm had}$ ee	$2\ell 0\tau_{\rm had}$ $e\mu$	$2\ell 0\tau_{\rm had}$ $\mu\mu$	$2\ell 1\tau_{\rm had}$	3ℓ	4ℓ
$t\bar{t}W$	2.9 ± 0.7	9.1 ± 2.5	6.6 ± 1.6	0.8 ± 0.4	6.1 ± 1.3	—
$t\bar{t}(Z/\gamma^*)$	1.55 ± 0.29	4.3 ± 0.9	2.6 ± 0.6	1.6 ± 0.4	11.5 ± 2.0	1.12 ± 0.20
Diboson	0.38 ± 0.25	2.5 ± 1.4	0.8 ± 0.5	0.20 ± 0.15	1.8 ± 1.0	0.04 ± 0.04
Non-prompt leptons	12 ± 6	12 ± 5	8.7 ± 3.4	1.3 ± 1.2	20 ± 6	0.18 ± 0.10
Charge misreconstruction	6.9 ± 1.3	7.1 ± 1.7	—	0.24 ± 0.03	—	—
Other	0.81 ± 0.22	2.2 ± 0.6	1.4 ± 0.4	0.63 ± 0.15	3.3 ± 0.8	0.12 ± 0.05
Total background	25 ± 6	38 ± 6	20 ± 4	4.8 ± 1.4	43 ± 7	1.46 ± 0.25
$t\bar{t}H$ (SM)	2.0 ± 0.5	4.8 ± 1.0	2.9 ± 0.6	1.43 ± 0.31	6.2 ± 1.1	0.59 ± 0.10
Data	26	59	31	14	46	0

ATLAS $t\bar{t}H(WW^{(*)},ZZ^{(*)},\tau\tau)$ - Backgrounds & VRs

- Backgrounds include:
  - **Electron mis-ID** → Mainly $2\ell 0/1\tau_{had}$ channels. Trident process ($e^{+/-} \rightarrow e^{+/-} \gamma \rightarrow e^{+/-} e^{-/+} e^{+/-}$). Data-driven estimate.
  - **Non-prompt leptons** from semileptonic b-hadron decay → **mostly $t\bar{t}$** → data driven estimate.
  - **$t\bar{t}W$, $t\bar{t}Z$, diboson** → Estimated from MC.
  - **τ_{had} mis-reconstruction** → estimated from MC and normalised to data in CR.

ATLAS $t\bar{t}H(WW^{(*)},ZZ^{(*)},\tau\tau)$ - Backgrounds & VRs

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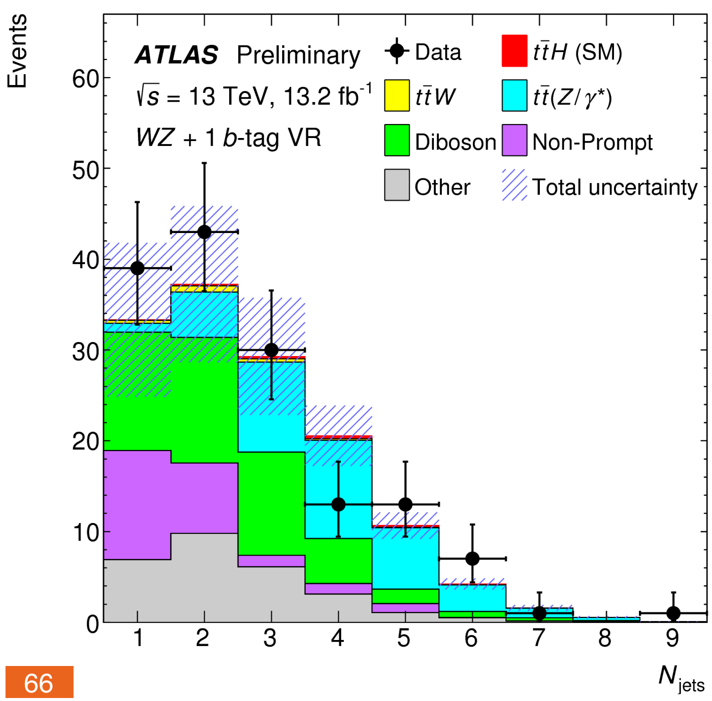
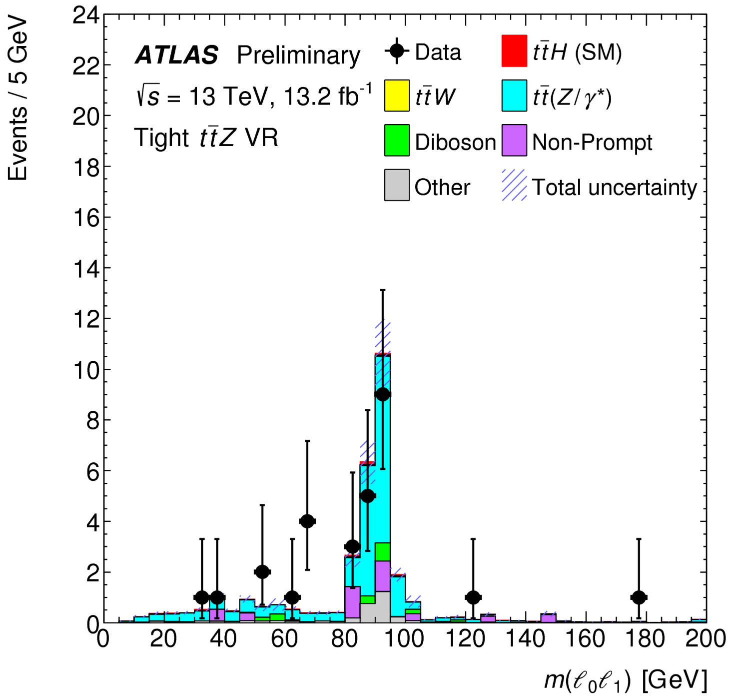
ATLAS-CONF-2016-058

- **$t\bar{t}W$, $t\bar{t}Z$, diboson backgrounds with prompt leptons** studied in control regions.
- Allow checks of normalisation and jet multiplicity.

VR	Purity	Expected	Data
Tight $t\bar{t}Z$	68%	32 ± 4	28
Loose $t\bar{t}Z$	58%	91 ± 12	89
WZ + 1 b-tag	33%	137 ± 27	147
$t\bar{t}W$	22%	51 ± 10	55

- "Purity": # events in VR expected to arise from the targeted process.





ATLAS $t\bar{t}H(WW^{(*)},ZZ^{(*)},\tau\tau)$ - Validation Regions

SR/VR	Channel	Selection criteria
VR	Tight $t\bar{t}Z$	3ℓ lepton selection At least one $\ell^+\ell^-$ pair with $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert < 10$ GeV $N_{\text{jets}} \geq 4$ and $N_{b-\text{jets}} \geq 2$
VR	Loose $t\bar{t}Z$	3ℓ lepton selection At least one $\ell^+\ell^-$ pair with $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert < 10$ GeV $N_{\text{jets}} \geq 4$ and $N_{b-\text{jets}} \geq 1$, or $N_{\text{jets}} = 3$ and $N_{b-\text{jets}} \geq 2$
VR	$WZ + 1$ b-tag	3ℓ lepton selection At least one $\ell^+\ell^-$ pair with $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert < 10$ GeV $N_{\text{jets}} \geq 1$ and $N_{b-\text{jets}} = 1$
VR	$t\bar{t}W$	$2\ell 0\tau_{\text{had}}$ lepton selection $2 \leq N_{\text{jets}} \leq 4$ and $N_{b-\text{jets}} \geq 2$ $H_{\text{T,jets}} > 220$ GeV for ee and $e\mu$ events $E_{\text{T}}^{\text{miss}} > 50$ GeV and ($m(ee) < 75$ or $m(ee) > 105$ GeV) for ee events

CMS $t\bar{t}H(WW^{(*)}, ZZ^{(*)}, \tau\tau)$ - Lepton BDT

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- BDT used to distinguish between prompt signal leptons and non-prompt and spurious leptons.
- Inputs include observables from: reconstructed leptons, clustered energy deposits charged particles in cone around lepton direction.
- Jet reconstruction and b-tagging algorithms are run on these and their output is used as inputs to train the algorithm.
- $t\bar{t}H$ vs $t\bar{t}$ (validated using data in CRs).
- "Tight" leptons selected if they pass a given lepton BDT threshold.

CMS $t\bar{t}H(WW^{(*)},ZZ^{(*)},\tau\tau)$ - Region Contributions

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CMS PAS HIG-16-022

	$\mu\mu$	ee	eμ	3ℓ
$t\bar{t}W$	18.3 ± 0.9	6.8 ± 0.6	24.5 ± 1.1	12.2 ± 0.7
$t\bar{t}Z/\gamma^*$	5.8 ± 0.6	7.4 ± 0.6	15.3 ± 1.3	22.6 ± 1.0
Di-boson	1.4 ± 0.2	1.1 ± 0.2	2.6 ± 0.3	5.7 ± 0.4
tttt	0.8 ± 0.2	0.4 ± 0.1	1.5 ± 0.2	1.2 ± 0.1
tqZ	0.2 ± 0.3	0.4 ± 0.4	0.6 ± 0.6	2.7 ± 0.8
Rare SM bkg.	1.6 ± 0.3	0.5 ± 0.1	1.8 ± 0.1	0.3 ± 0.1
Charge mis-meas.		6.7 ± 0.1	10.0 ± 0.1	
Non-prompt leptons	33.4 ± 1.2	23.1 ± 1.1	61.9 ± 1.7	51.0 ± 1.8
All backgrounds	61.5 ± 1.7	46.4 ± 1.5	118.0 ± 2.5	95.7 ± 2.3
$t\bar{t}H$ ($H \to WW^*$)	6.3 ± 0.2	2.6 ± 0.1	8.5 ± 0.2	8.0 ± 0.2
$t\bar{t}H$ ($H \to \tau\tau$)	1.6 ± 0.1	0.7 ± 0.1	2.5 ± 0.1	2.1 ± 0.1
$t\bar{t}H$ ($H \to ZZ^*$)	0.2 ± 0.0	0.1 ± 0.0	0.3 ± 0.0	0.5 ± 0.0
Data	74	45	154	105

Expected and observed yields after the selection in 2LSS and 3L final states. The rare SM backgrounds include $W^{\pm}W^{\pm}qq'$, WW produced in double-parton interactions, and triboson production. Uncertainties are purely statistical. The backgrounds from non-prompt leptons and charge mis-measurements are extracted from data.

CMS $t\bar{t}H(WW^{(*)},ZZ^{(*)},\tau\tau)$ - Event categorisation

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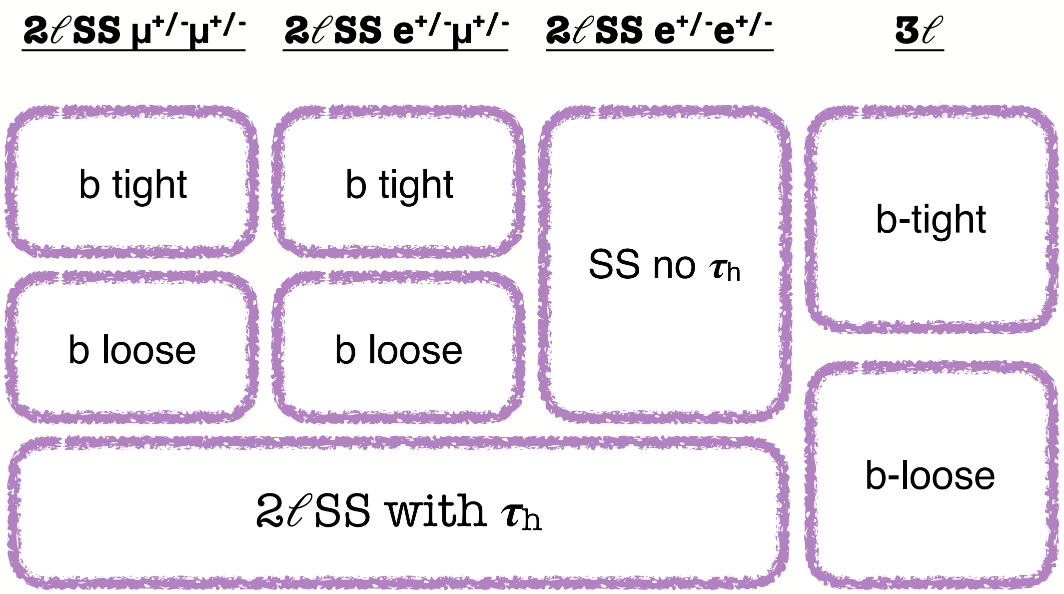
CMS PAS HIG-16-022

- **2ℓSS separated according flavour of leptons.**
- **2ℓSS** with τ_h separated out: **H→ττ enriched** region.
- **2ℓSS with μ and no τ_h and 3ℓ events divided into "b tight" ("b loose")**: ≥2 jets pass medium (minimum) b-tagger requirements.
- **BDT** discriminant in each region.
  - 2 trained: 1 against $t\bar{t}$ and another against $t\bar{t}V$ which are then combined.
  - **3ℓ BDT includes MEM weights for $t\bar{t}H$ and $t\bar{t}V$ as input**
- The output of the BDT discriminators is used simultaneously to divide each category in bins of different S/B.
- The signal extraction is performed by fitting its normalisation from the distribution of events among these bins.



CMS $t\bar{t}H(WW^{(*)},ZZ^{(*)},\tau\tau)$ - Results

2015 data CMS PAS HIG-15-008

Category	μ best fit $\pm 1\sigma$	Observed limit	Expected limit $\pm 1\sigma$
same-sign dileptons	$-0.5\ (+1.0)\ (-0.7)$	2.1	$2.7\ (+1.4)\ (-0.9)$
trileptons	$5.8\ (+3.3)\ (-2.7)$	11.7	$5.4\ (+2.9)\ (-1.8)$
combined	$0.6\ (-1.1)\ (+1.4)$	3.3	$2.6\ (+1.3)\ (-0.8)$

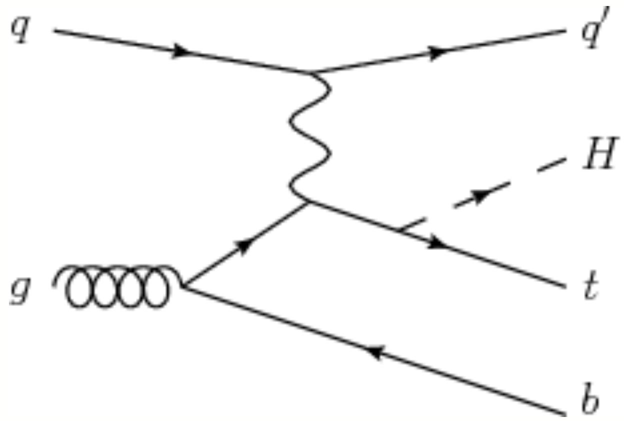
2016 data CMS PAS HIG-16-022

Category	Obs. limit	Exp. limit $\pm 1\sigma$	Best fit $\mu \pm 1\sigma$
Same-sign dileptons	4.6	$1.7^{+0.9}_{-0.5}$	$2.7^{+1.1}_{-1.0}$
Trileptons	3.7	$2.3^{+1.2}_{-0.7}$	$1.3^{+1.2}_{-1.0}$
Combined categories	3.9	$1.4^{+0.7}_{-0.4}$	$2.3^{+0.9}_{-0.8}$
Combined with 2015 data	3.4	$1.3^{+0.6}_{-0.4}$	$2.0^{+0.8}_{-0.7}$

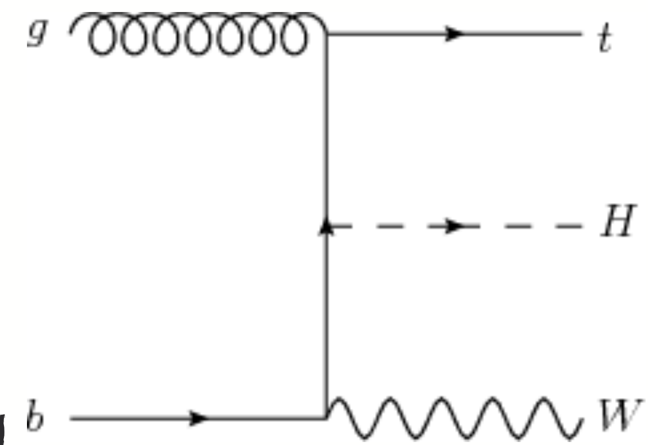
- Reported **95% CL upper limit** on signal production cross-section = **3.4** x SM.
- Expected **95% CL upper limit under the B only** hypothesis = **1.3**.
- 2015+2016 results combined **best-fit μ = 2.0.**

tH Production Processes

tHqb t-channel

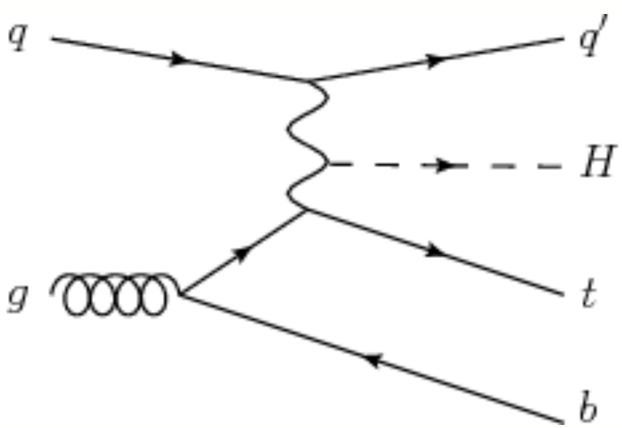


tHqb Wt-channel



- NOTE: s-channel production neglected in note due much to smaller production cross-section

WtH t-channel



WtH Wt-channel