Observation the Higgs Boson produced in association with top quarks

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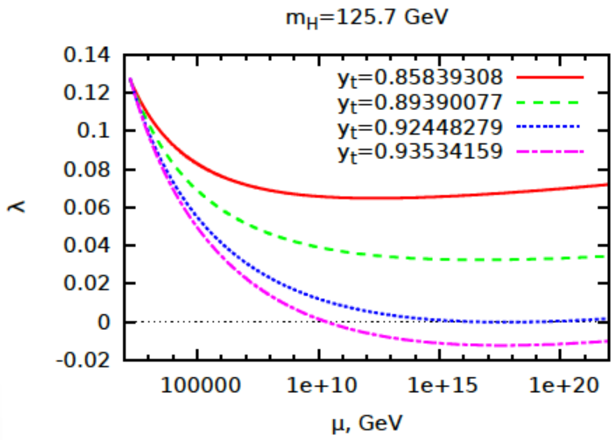
On behalf of the ATLAS and CMS collaborations

Kruger, 2018

Motivation

- Evidence for the Higgs coupling to fermions is a milestone in Higgs studies
- Top Yukawa coupling is the most important one:
  - Strongest coupling of the Standard Model, ~1
  - Sensitive to New Physics
  - Significant role in EW vacuum stability:

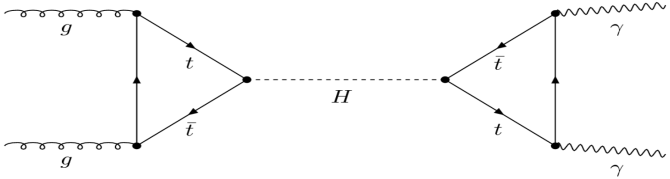
    Running of Higgs self coupling (λ) sensitive to Top Yukawa coupling (y_t)



F. Bezrukov, M. Shaposhnikov
M. J. Exp. Theor. Phys. (2015) 120: 335.

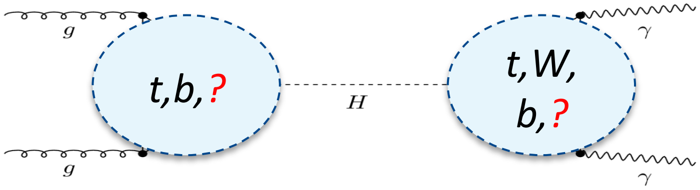
Motivation

- y_t can be determined:
  - From Top mass measurement
  - From Higgs production and γγ decay



Motivation

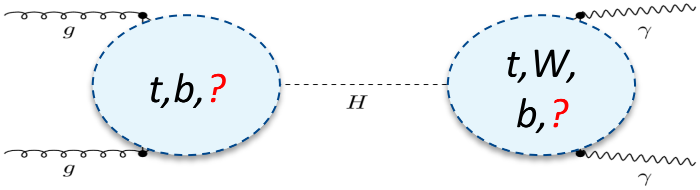
- y_t can be determined:
  - From Top mass measurement
  - From Higgs production and $\gamma\gamma$ decay



Sensitive to New Physics contributions

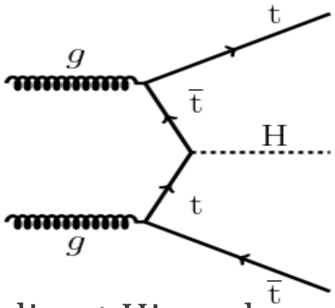
Motivation

- y_t can be determined:
  - From Top mass measurement
  - From Higgs production and γγ decay



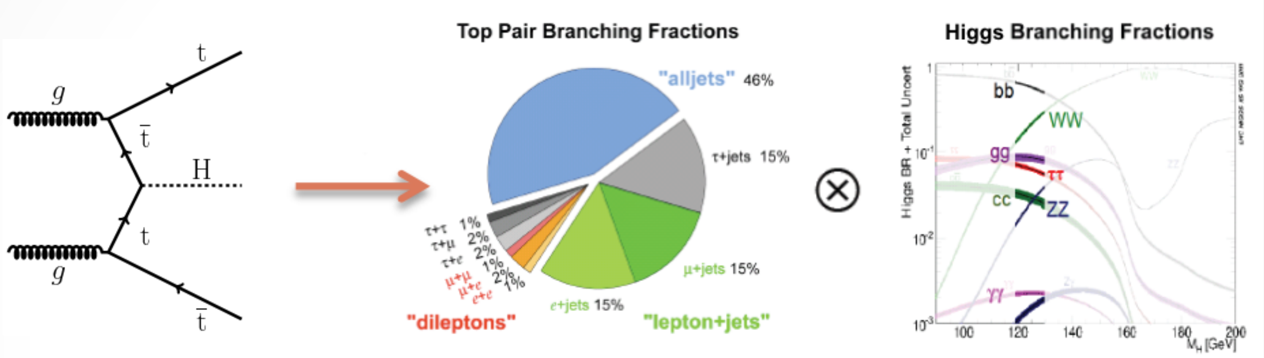
Sensitive to New Physics contributions

  - From ttH production
    - provide direct evidence of the existence of y_t
    - Measurement at tree level



- The only Higgs coupling that cannot be observed from direct Higgs decay

ttH signatures

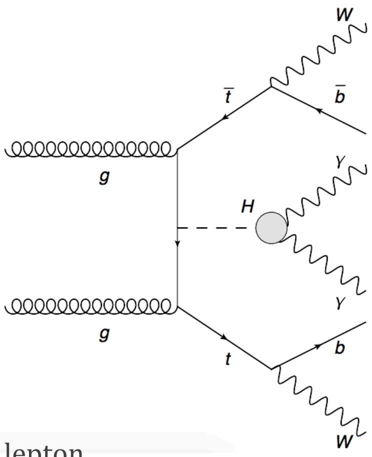


- ttH final state combines top pair decay signature and Higgs decay signature → large number of possible final states
- 3 families of signatures

	ATLAS	CMS
2γ (H→γγ)	79.8 fb^{-1} arXiv:1806.00425	35.9+41.5 fb^{-1} CMS-HIG-16-040 CMS-HIG-18-018
Multi *b* (H→*bb*)	36.1 fb^{-1} arXiv:1712.08895	35.9 fb^{-1} CMS-HIG-17-026 CMS-HIG-17-022
b+leptons (H→WW*, ZZ*, ττ)	36.1 fb^{-1} arXiv:1712.08891 (79.8 fb^{-1} arXiv:1806.00425)	35.9+41.5 fb^{-1} CMS-HIG-17-018 CMS-HIG-18-019
		Combination 35.9 fb^{-1} CMS-HIG-17-031

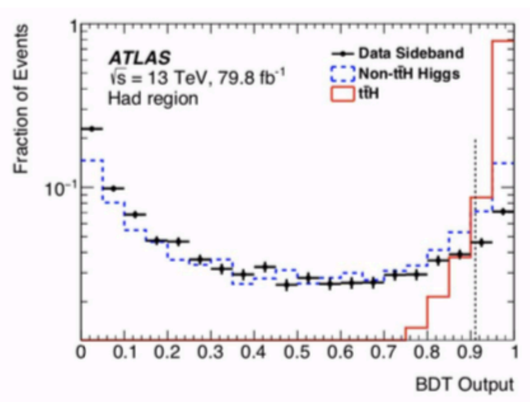
ttH (H→γγ)

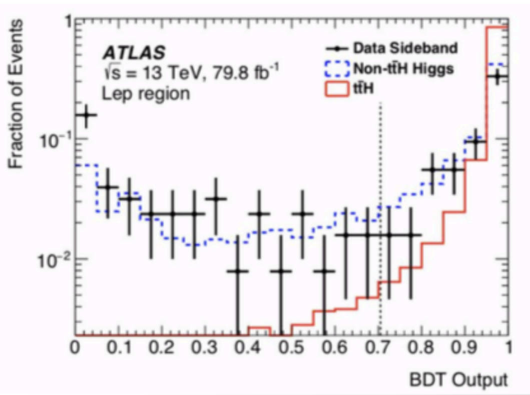
- Small BR compensated by small backgrounds and good diphoton mass resolution



- Signature and categories:
  - Driven by tt decay mode
  - Hadronic category:
    - High jet and *b*-tag multiplicities
  - Leptonic category:
    - One or more high quality charged lepton

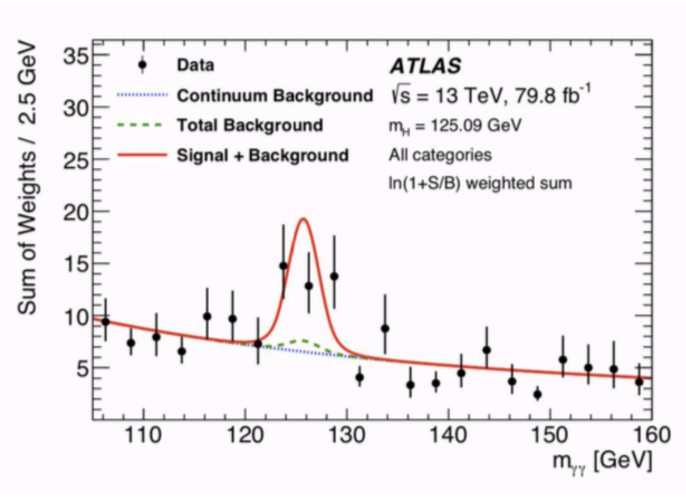
- Two BDTs used to split hadronic and leptonic regions:
  - Trained with object-level variables (leptons, jets, MET, photon momenta)
  - Independent from $m_{\gamma\gamma}$ (the final discriminant)





ttH (H→γγ)

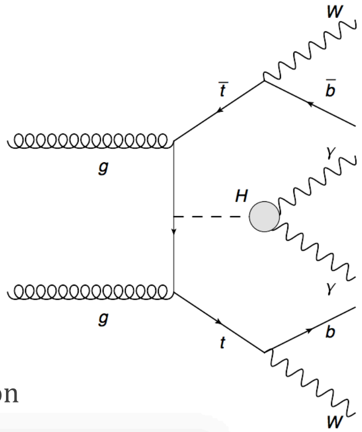
- Analysis strategy:
  - Categorize events depending on the value of the BDT response
    - 4 categories for the hadronic channel
    - 3 categories for the leptonic channel
  - Discriminant parameter: $m_{\gamma\gamma}$
  - Signal modelling based on MC simulation
  - Higgs background (MC simulation)
  - Continuum background – data driven for each category



- Dominant systematic uncertainties:
  - MC modelling
  - Continuum background modelling
  - Photon energy scale

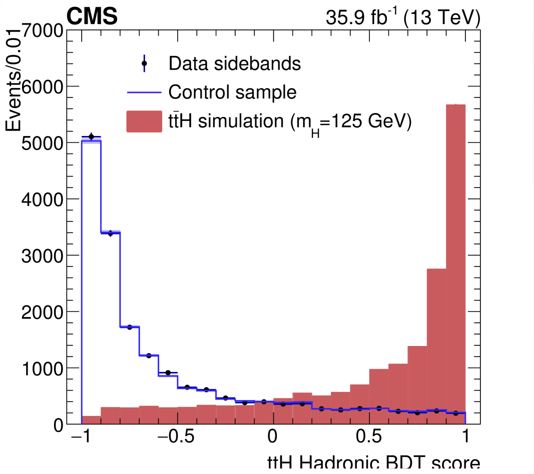
ttH (H→γγ)

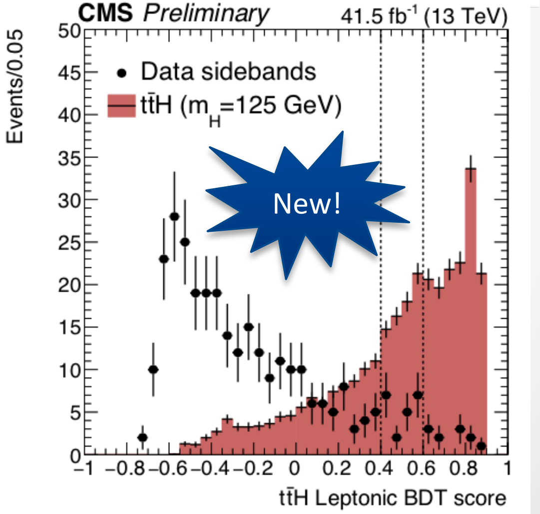
- Small BR compensated by small backgrounds and good diphoton mass resolution



- Signature and categories:
  - Driven by tt decay mode
  - Hadronic category:
    - High jet and *b*-tag multiplicities
  - Leptonic category:
    - One or more high quality charged lepton

- BDT used to reject background in Hadronic (2015-16) category. Two BDTs used to create regions in hadronic and leptonic categories (2017):
  - Combines photon, lepton, jet properties and global variables. Independent from mγγ

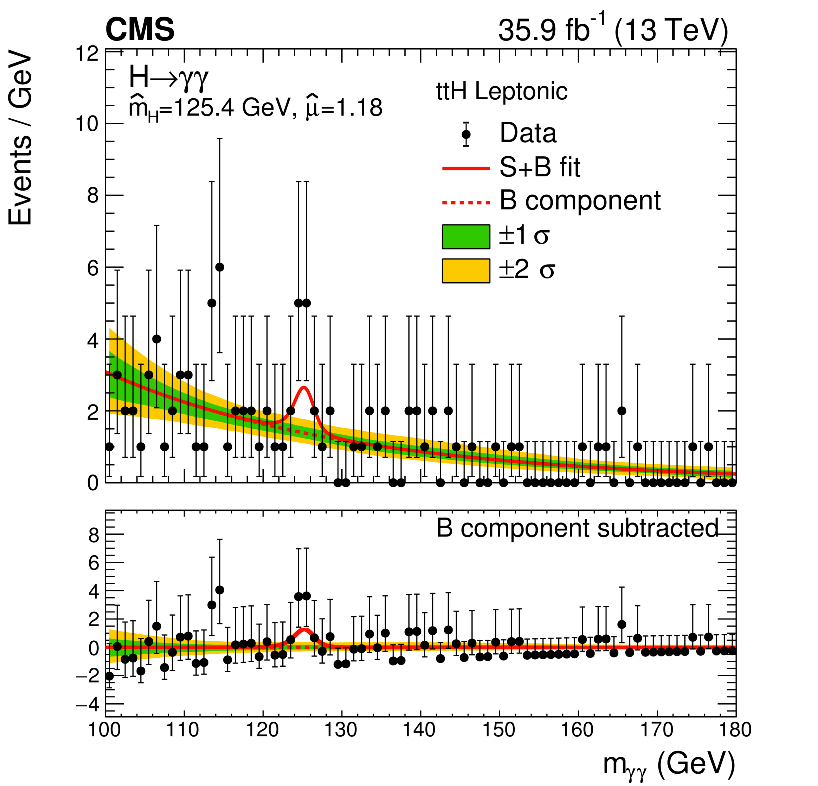




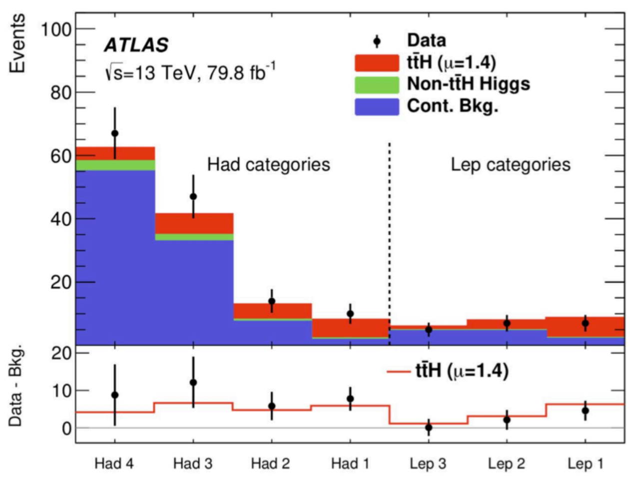
ttH (H→γγ)

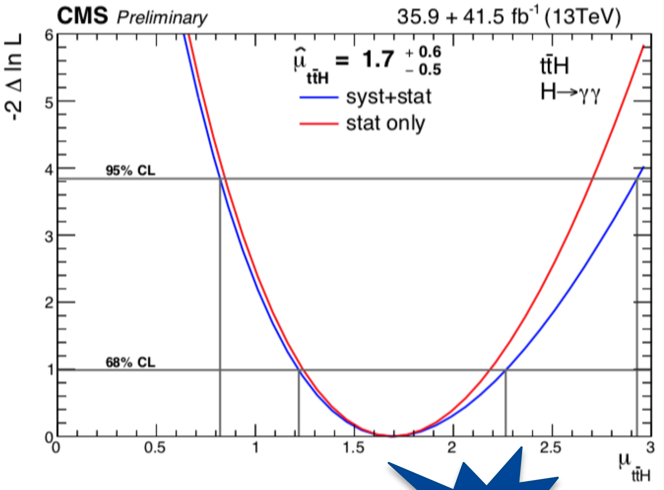
- Analysis strategy:
  - Two categories: leptonic / hadronic
  - Discriminant parameter: $m_{\gamma\gamma}$
  - Signal modelling based on MC simulation
  - Higgs background (MC simulation)
  - Continuum background – data driven

- Dominant systematic uncertainties:
  - MC modelling
  - Continuum background modelling
  - Photon energy scale



ttH (H→γγ)





	ATLAS	CMS
Signal strength	1.4 +0.5/-0.4	1.7 +0.6/-0.5
Significance	4.1 σ (3.7 σ expected)	4.1 σ (2.7 σ expected)

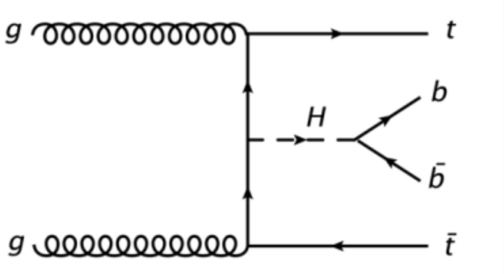
Results are statistically limited

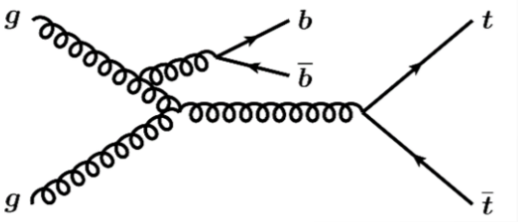
ttH (4*b*)

- Benefits from the large H → bb branching ratio
- Large and challenging background due to tt+HF:
  - Challenging modelling
  - Assess the corresponding uncertainties

- Channels:
  - Di-leptonic channel
  - Semi-leptonic channel
  - Fully Hadronic channel (only CMS for Run 2)

- Use number of jets, *b*-tag score of the jets and leptons to create categories



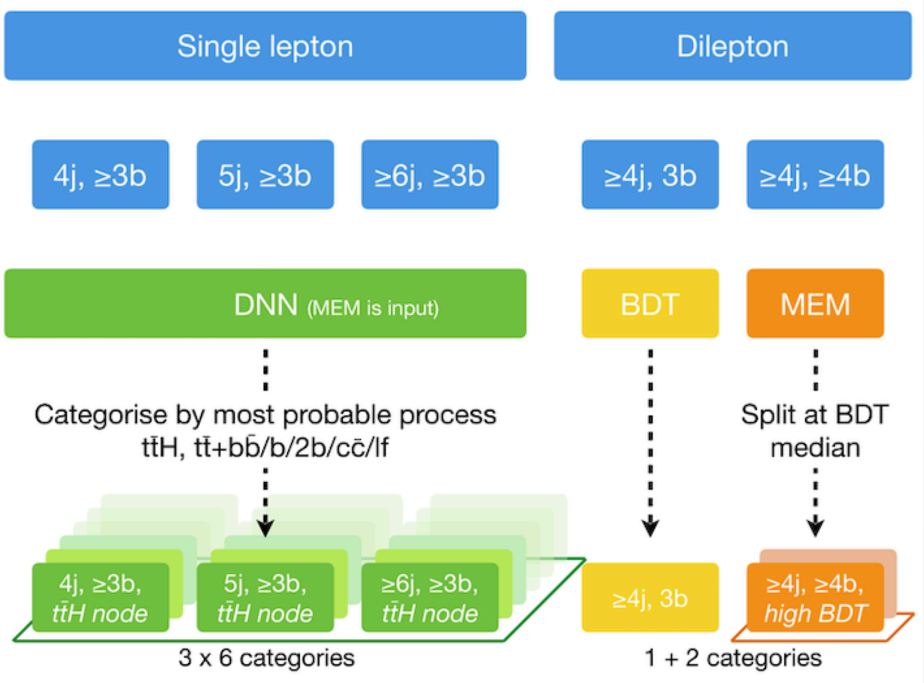


ttH (4*b*, leptonic)

- Analysis strategy:

    - Signal regions of different significances defined using number of jets and *b*-tagged jets
    - tt+HF modelling: Breakdown of tt+HF events based on flavours
    - Use of Matrix Element Method against tt+HF as input in MVA for one of the two dileptonic regions
    - Control and signal regions fitted simultaneously to constrain the systematic uncertainties

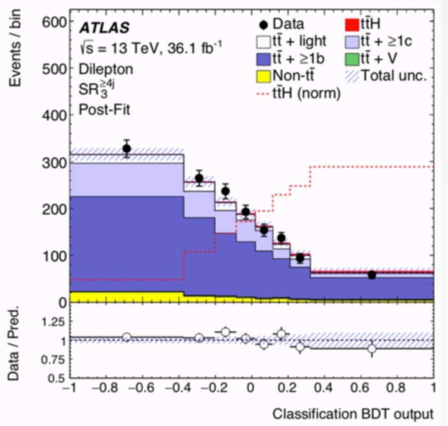
- Final discriminant: classification BDT (dilepton), DNN (single lepton)

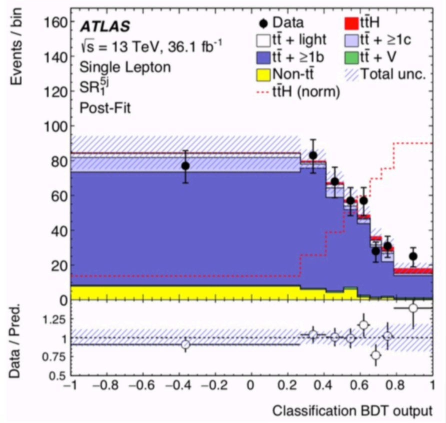


ttH (4*b*, leptonic)

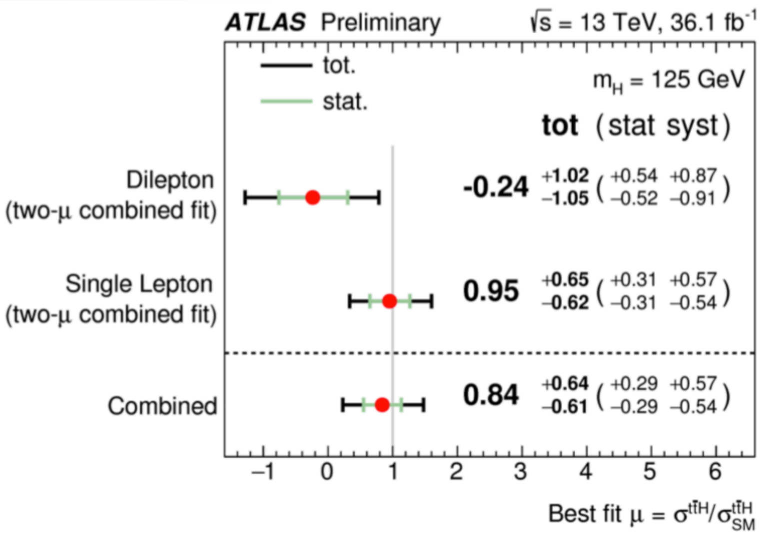
- Analysis strategy:
  - Signal regions of different significances defined using number of jets, *b*-tag score of the jets and number of leptons
  - Use a cascade of MVA classifiers
  - Control (10) and signal (9) regions fitted simultaneously to constrain the systematic uncertainties
  - tt+HF modelling: Breakdown of tt+HF events based on flavours

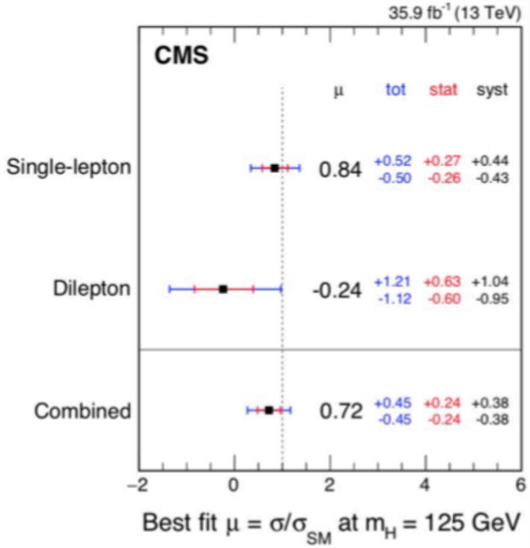
- Final discriminant: BDT classifier
  - Different BDTs combines different inputs per region
  - Inputs obtained after event reconstructions (BDT, Likelihood or MEM):
    ttH system reconstruction BDT score, kinematic of reconstructed Higgs and
    Top, event variables, *b*-tag, …





ttH (4*b*, leptonic)



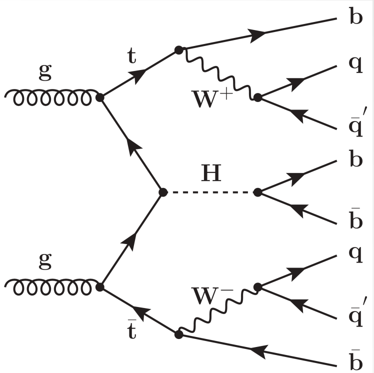


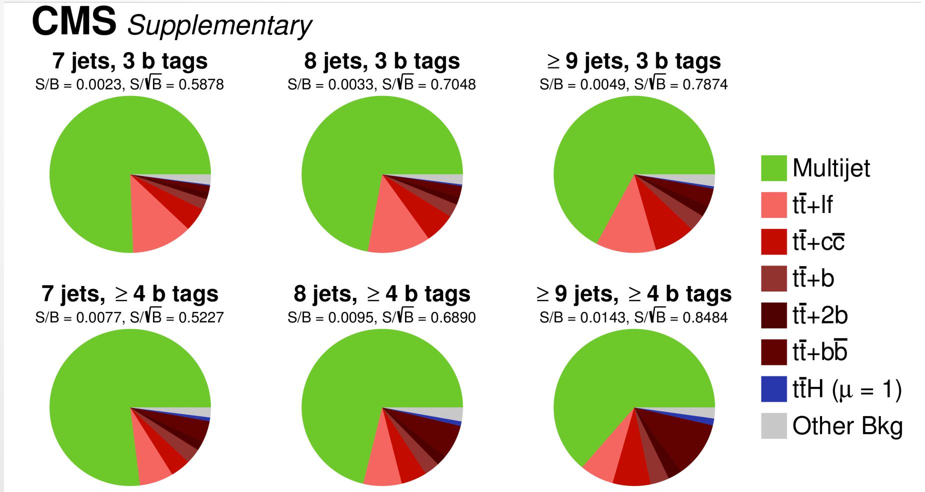
	ATLAS	CMS
Signal strength	0.84 +0.64/-0.61	0.72 +0.45/-0.45
Significance	1.4 σ (1.6 σ expected)	1.6 σ (2.2 σ expected)

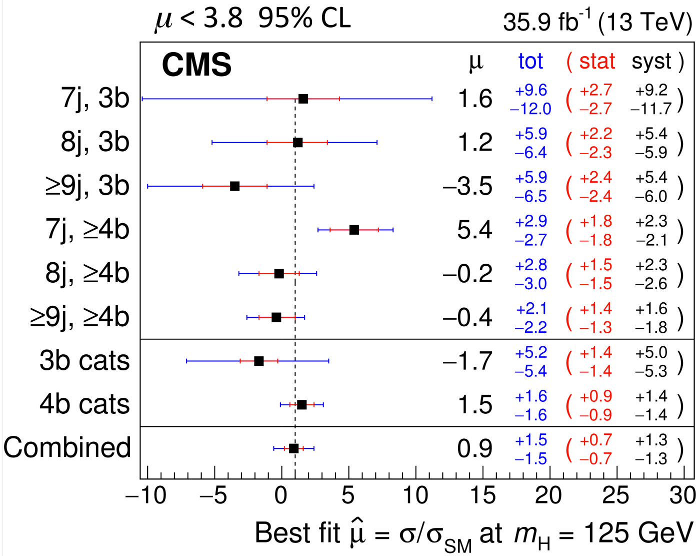
- Large systematics due to tt+*bb* modelling and *b*-tagging
- Additional tt+HF systematic in ATLAS

ttH (4b, hadronic)

- Analysis strategy
  - Signal regions of different significances defined using number of jets and *b*-tagged jets
  - Main background: QCD-multijet
  - Use of Matrix Element Method against tt+HF and as final discriminant

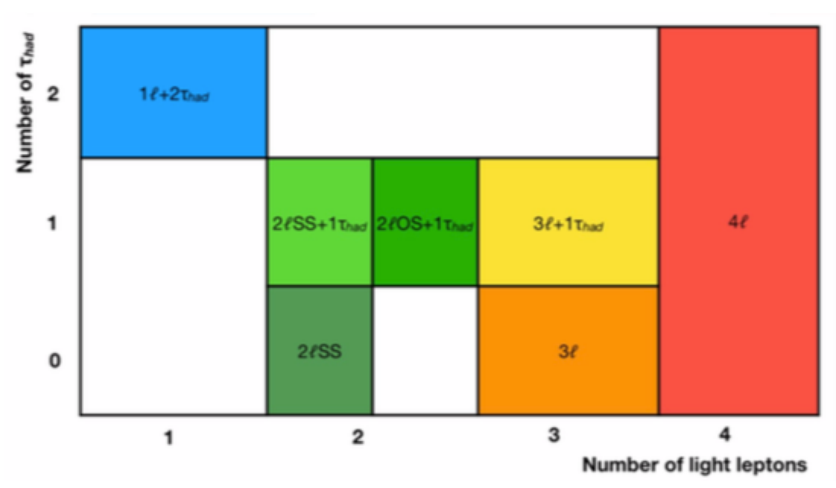




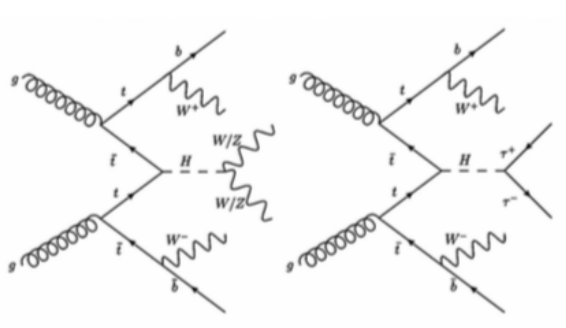


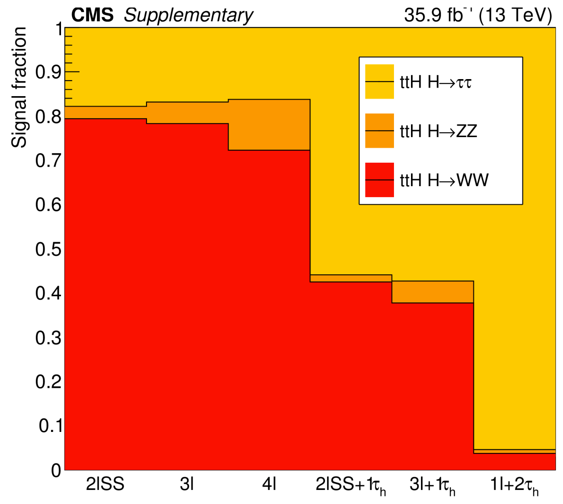
ttH (multileptons)

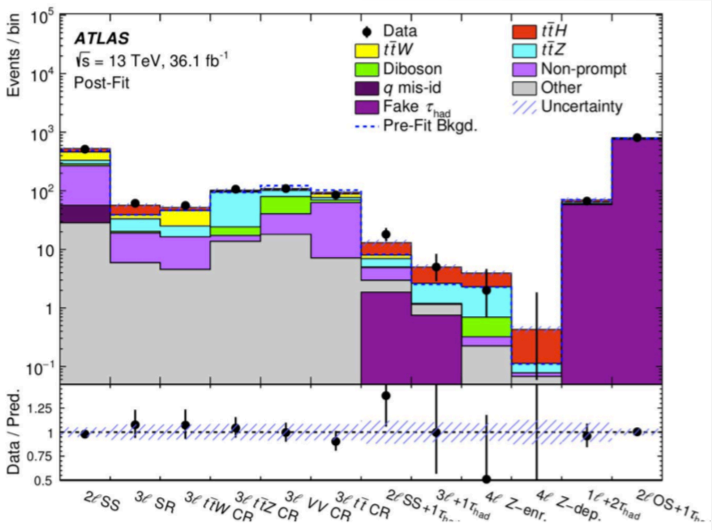
- Mainly probe H → W^+W^-, H → ZZ and H → $\tau^+\tau^-$
- Channels defined by number of leptons and hadronic τ



- $2\ell+2\tau$ channel in CMS in 2017data analysis
- Main background:
  - Irreducible backgrounds: ttV
  - Non –prompt leptons







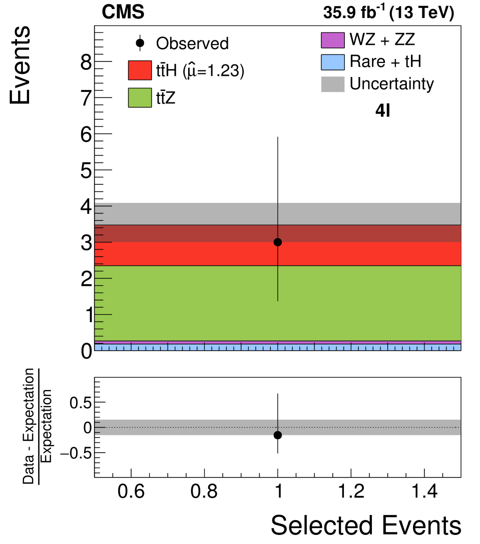
ttH (multileptons)

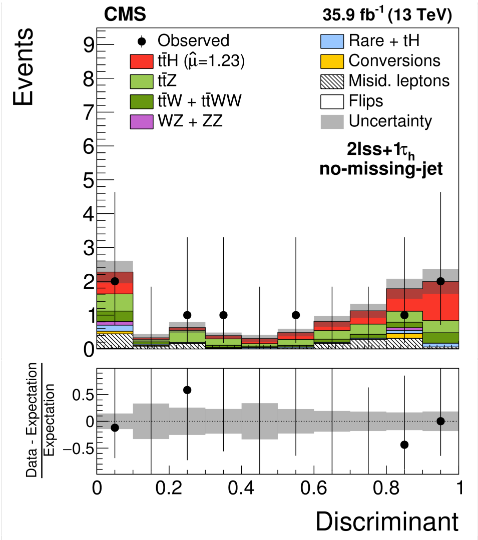
- Analysis strategy:
  - Counting experiment in $3\ell+1\tau$, 4ℓ (BDT)
  - Multivariate shape (BDT) in 5 signal regions
- Background estimate:
  - Non prompt leptons, conversions (e, μ, τ) from data
  - ttW, ttZ: Monte Carlo simulation
- Simultaneous fit of signal and control regions

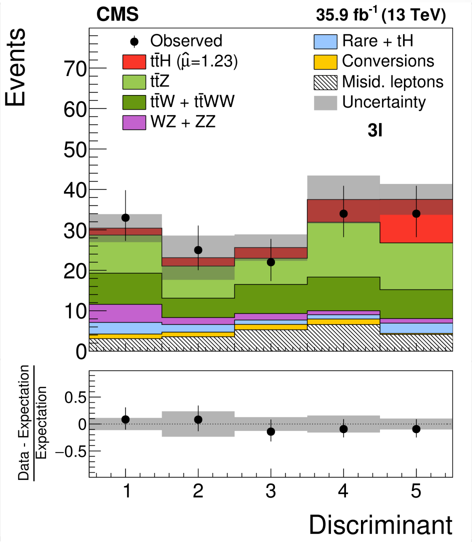
	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{had}$	$2\ell SS+1\tau_{had}$	$2\ell OS+1\tau_{had}$	$3\ell+1\tau_{had}$
BDT trained against	Fakes and $t\bar{t}V$	$t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, VV	$t\bar{t}Z$ / -	$t\bar{t}$	all	$t\bar{t}$	-
Discriminant	2×1D BDT	5D BDT	Event count	BDT	BDT	BDT	Event count
Number of bins	6	5	1 / 1	2	2	10	1
Control regions	-	4	-	-	-	-	-

ttH (multileptons)

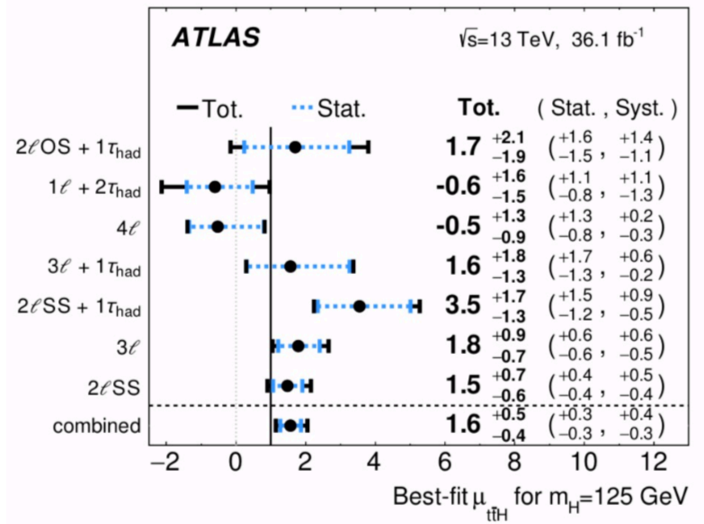
- Analysis strategy :
  - Counting experiment in 4ℓ
  - MEM as discriminant in $2\ell+1\tau$
  - Multivariate (BDT) as discriminant in the other signal regions
- Background estimate:
  - Non prompt leptons (e, μ, τ) from data. Photon conversion : Monte Carlo simulation
  - ttW, ttZ: floating

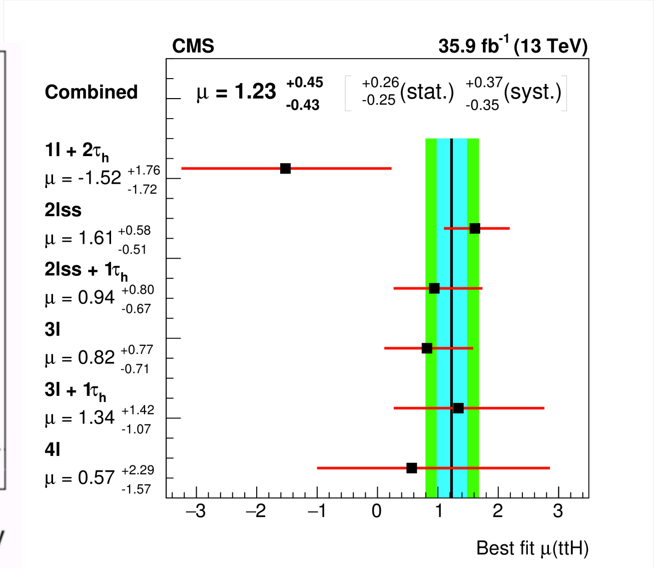






ttH (multileptons)

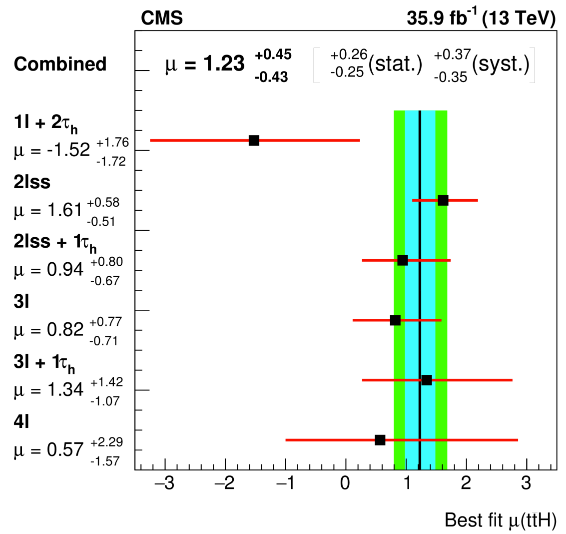


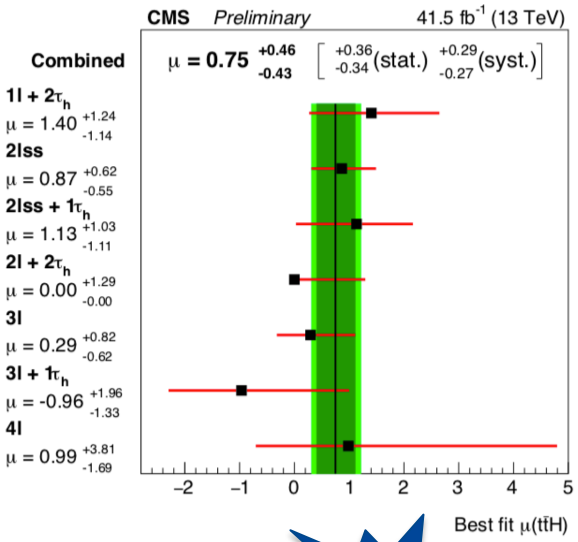


	ATLAS (2015-16)	CMS (2015-16)
Signal strength	1.6 +0.5/-0.4	1.23 +0.45/-0.43
Significance	4.1σ (2.8σ expected)	3.2σ (2.8 expected)

- Comparable statistical and systematic uncertainties
- Main systematic uncertainties: non-prompt leptons, JES, ttH and ttV modellings

ttH (multileptons)

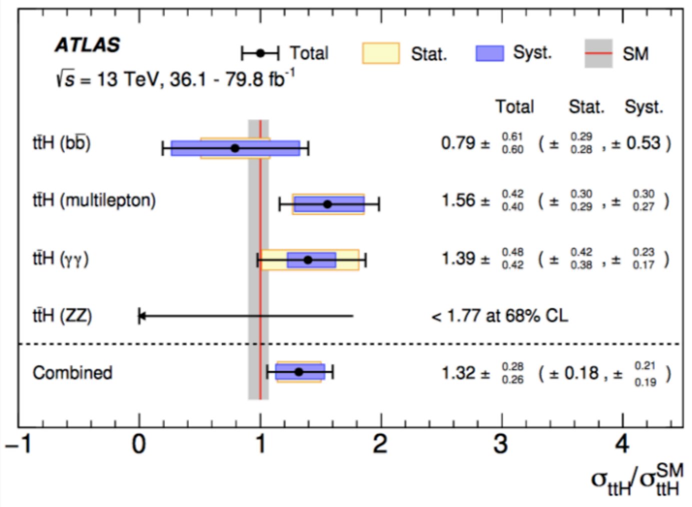


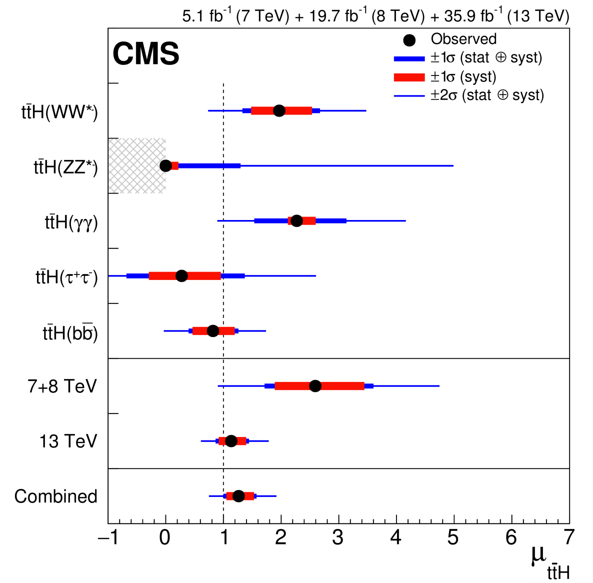


New!

	CMS (2015-16)	CMS (2017)	CMS (2015-17)
Signal strength	1.23 +0.45/-0.43	0.75 +0.46/0.43	0.96 +0.34/-0.31
Significance	3.2σ (2.8σ expected)	1.7σ (2.9σ expected)	3.2σ (4.0σ expected)

Combining ttH Results



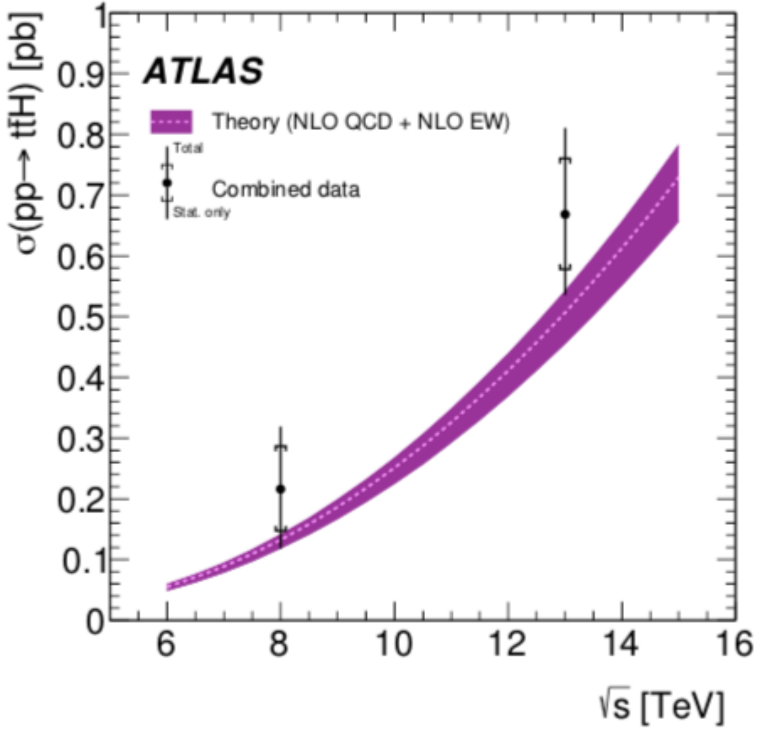


	ATLAS	CMS
Signal strength (Run 2)	1.32 +0.28/-0.26	1.14 +0.31/-0.27
Significance (Run 2)	5.8 σ (4.9 σ expected)	4.5 σ (4.2 σ expected)
Signal strength (Run 1+2)		1.26 +0.31/-0.26
Significance (Run 1+2)	6.3 σ (5.1 σ expected)	5.2 σ (4.2 σ expected)

Conclusion

- ATLAS and CMS experiments reported two independent observations of the ttH production mode
- Significant improvements of the analyses were realised since Run 1
- Main uncertainties related to non-prompt leptons, modelling of the ttV, tt+HF
- Weight of the various channels will evolve with luminosity
- Analysis of the full Run-2 dataset will allow to go for a more precise measurement of ttH production cross-section

Additional Material


ATLAS
Theory (NLO QCD + NLO EW)
Total
Combined data
Stat. only
σ(pp→ tt̄H) [pb]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
6
8
10
12
14
16
√s [TeV]

MVA Variables in multileptons

Category	$1\ell + 2\tau_h$	$2\ell ss + 1\tau_h$	$2\ell + 2\tau_h$	$3\ell + 1\tau_h$	$2\ell ss$		3ℓ	
					$t\bar{t}$	$t\bar{t}V$	$t\bar{t}$	$t\bar{t}V$
Leading ℓ cone p_T	X		X	X		X		X
Trailing ℓ cone p_T		X		X		X		X
Minimum of ΔR(leading ℓ, j)	X	X	X	X	X	X	X	X
Minimum of ΔR(trailing ℓ, j)		X			X	X	X	X
ΔR(leading ℓ, trailing ℓ		X		X				
Transverse Mass of leading ℓ	X	X			X	X	X	X
Transverse Mass of trailing ℓ		X						
Maximum $\lvert\eta\rvert$ of ℓ collection		X		X	X	X	X	X
Signal leading $\ell \times$ signal trailing ℓ			X					
Average of $\Delta R(jj)$	X	X	X					
Number of jets ($p_T > 25$ GeV)		X		X	X	X	X	X
Number of loose b-jets	X		X					
Mass of leading medium b-jet pair		X						
Mass of leading loose b-jet pair				X				
E_T^{miss}	X	X		X				
res-hTT	X	X						
Hadronic t p_T	X	X						
$\mathcal{D}_{thad}^{max}$					X			
$\mathcal{D}_{Hj}^{max}$						X		
Leading τ_h p_T	X	X	X	X				
Trailing τ_h p_T	X		X					
Mass of leading τ_h + trailing τ_h	X		X					
ΔR(leading τ_h, trailing τ_h)	X		X					
$cos(\theta)^*$(leading τ_h, trailing τ_h)	X		X					
Minimum of ΔR(leading τ_h, j)	X	X		X				
Minimum of ΔR(trailing τ_h, j)	X							
Minimum of $\Delta R(\tau_h, j)$			X					
Mass of leading ℓ+ leading τ_h				X				
Mass of trailing ℓ+ leading τ_h		X		X				
ΔR(leading ℓ, leading τ_h)	X	X						
ΔR(trailing ℓ, leading τ_h)		X						
$\Delta R(\ell, \tau_h)$ for same-sign pair of (ℓ, τ_h)	X							
Average of $\Delta R(\ell, \tau_h)$			X					
MEM							X	X
Number of variables	17	18	13	12	6	8	6	8

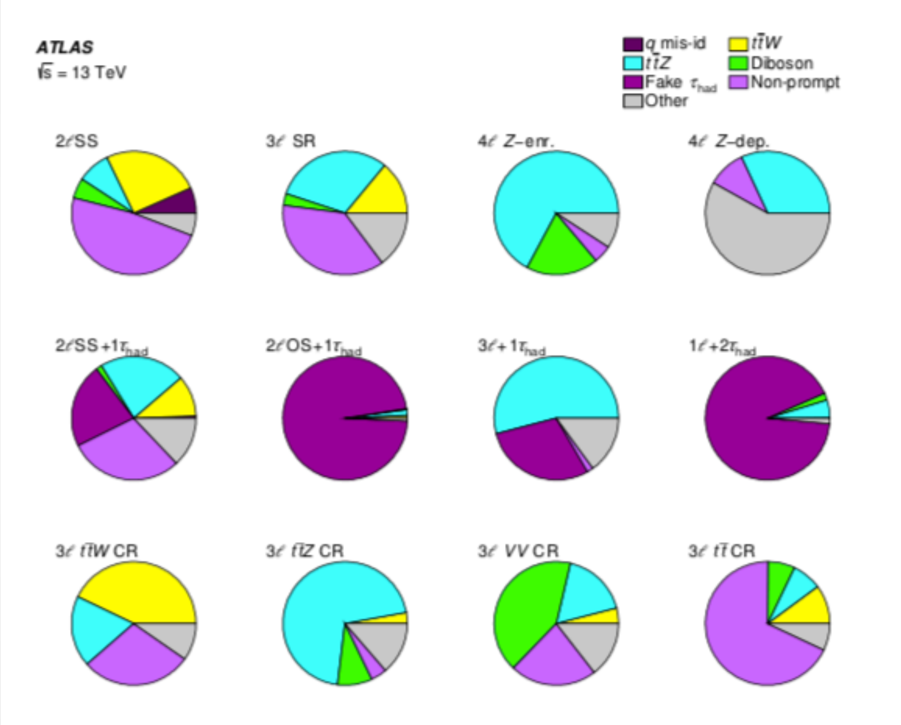
MVA variables in multileptons

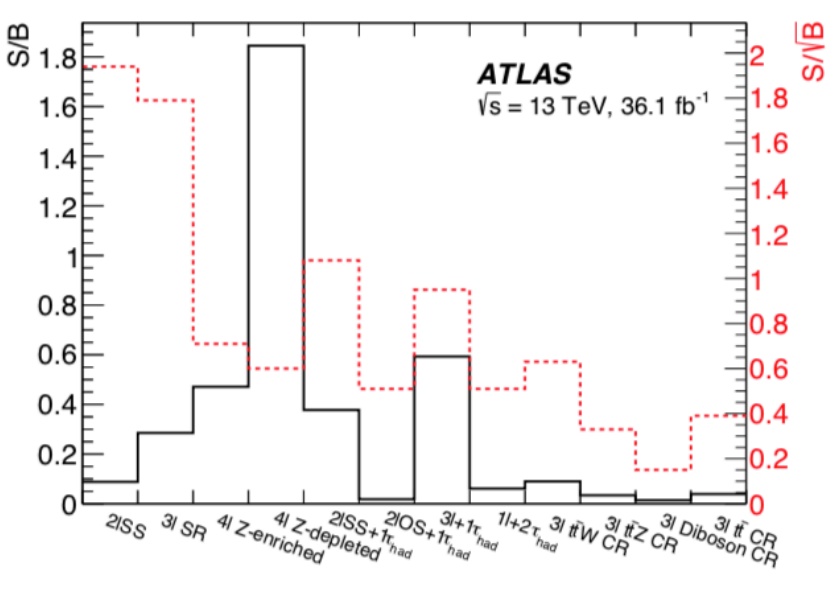
	Variable	$2\ell SS$	3ℓ	4ℓ	$1\ell+2\tau_{had}$	$2\ell SS+1\tau_{had}$	$2\ell OS+1\tau_{had}$
Lepton properties	Leading lepton p_T		×				
	Second leading lepton p_T	×	×			×	
	Third lepton p_T		×				
	Dilepton invariant mass (all combinations)	×	×*				×
	Three-lepton invariant mass		×				
	Four-lepton invariant mass			×			
	Best Z-candidate dilepton invariant mass			×			
	Other Z-candidate dilepton invariant mass			×			
	Scalar sum of all leptons p_T			×			×
	Second leading lepton track isolation					×	
	Maximum $\|\eta\|$ (lepton 0, lepton 1)	×				×*	
	Lepton flavor	×*	×*				
	Lepton charge		×				
Jet properties	Number of jets	×*	×*		×	×	×
	Number of b-tagged jets	×*	×*		×	×	×
	Leading jet p_T						×
	Second leading jet p_T		×			×*	
	Leading b-tagged jet p_T		×				
	Scalar sum of all jets p_T		×		×	×	×
	Scalar sum of all b-tagged jets p_T						×
	Has leading jet highest b-tagging weight?		×				
	b-tagging weight of leading jet		×				
	b-tagging weight of second leading jet		×			×	
	b-tagging weight of third leading jet					×	
	Pseudorapidity of fourth leading jet					×	
τ_{had}	Leading τ_{had} p_T				×		×
	Second leading τ_{had} p_T				×		
	Di-τ_{had} invariant mass				×		
	Invariant mass τ_{had}–furthest lepton					×	

MVA variables in multileptons

	Variable	$2\ell SS$	3ℓ	4ℓ	$1\ell+2\tau_{had}$	$2\ell SS+1\tau_{had}$	$2\ell OS+1\tau_{had}$
Angular distances	ΔR(lepton 0, lepton 1)		×				
	ΔR(lepton 0, lepton 2)		×				
	ΔR(lepton 0, closest jet)	×	×				
	ΔR(lepton 0, leading jet)		×			×	
	ΔR(lepton 0, closest b-jet)		×				
	ΔR(lepton 1, closest jet)	×	×				
	ΔR(lepton 2, closest jet)		×				
	Smallest ΔR(lepton, jet)		×				×
	Smallest ΔR(lepton, b-tagged jet)						×
	Smallest ΔR(non-tagged jet, b-tagged jet)						×
	ΔR(lepton 0, τ_{had})						×
	ΔR(lepton 1, τ_{had})						×
	Minimum ΔR between all jets				×		
	ΔR between two leading jets					×	
$\vec{p}_T^{miss}$	Missing transverse momentum E_T^{miss}	×		×			
	Azimuthal separation $\Delta\phi$(leading jet, $\vec{p}_T^{miss}$)		×				
	Transverse mass leptons (H/Z decay) - $\vec{p}_T^{miss}$			×			
	Pseudo-Matrix-Element			×			

Control regions in multileptons





Preselection in multileptons

Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$
2ℓSS	Two very tight light leptons with $p_{\text{T}} > 20$ GeV Same-charge light leptons Zero medium τ_{had} candidates $N_{\text{jets}} \geq 4$ and $N_{b\text{-jets}} < 3$
3ℓ	Three light leptons with $p_{\text{T}} > 10$ GeV; sum of light-lepton charges ± 1 Two same-charge leptons must be very tight and have $p_{\text{T}} > 15$ GeV The opposite-charge lepton must be loose, isolated and pass the non-prompt BDT Zero medium τ_{had} candidates $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV for all SFOC pairs $\lvert m(3\ell) - 91.2\text{ GeV}\rvert > 10$ GeV
4ℓ	Four light leptons; sum of light-lepton charges 0 Third and fourth leading leptons must be tight $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV for all SFOC pairs $\lvert m(4\ell) - 125\text{ GeV}\rvert > 5$ GeV Split 2 categories: Z-depleted (0 SFOC pairs) and Z-enriched (2 or 4 SFOC pairs)
$1\ell+2\tau_{\text{had}}$	One tight light lepton with $p_{\text{T}} > 27$ GeV Two medium τ_{had} candidates of opposite charge, at least one being tight $N_{\text{jets}} \geq 3$
$2\ell\text{SS}+1\tau_{\text{had}}$	Two very tight light leptons with $p_{\text{T}} > 15$ GeV Same-charge light leptons One medium τ_{had} candidate, with charge opposite to that of the light leptons $N_{\text{jets}} \geq 4$ $\lvert m(ee) - 91.2\text{ GeV}\rvert > 10$ GeV for ee events
$2\ell\text{OS}+1\tau_{\text{had}}$	Two loose and isolated light leptons with $p_{\text{T}} > 25, 15$ GeV One medium τ_{had} candidate Opposite-charge light leptons One medium τ_{had} candidate $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV for the SFOC pair $N_{\text{jets}} \geq 3$
$3\ell+1\tau_{\text{had}}$	3ℓ selection, except: One medium τ_{had} candidate, with charge opposite to the total charge of the light leptons The two same-charge light leptons must be tight and have $p_{\text{T}} > 10$ GeV The opposite-charge light lepton must be loose and isolated

Preselection in multileptons

Selection	4ℓ
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to b\ell\nu$, $H \to WW \to \ell\nu\ell\nu$ $t \to b\ell\nu$, $t \to b\ell\nu$, $H \to ZZ \to \ell\ell qq$ or $\ell\ell\nu\nu$
Trigger	Single-, double- or triple-lepton triggers
Lepton multiplicity	≥ 4 leptons
Lepton p_T	$p_T > 25$ / 15 / 15 / 10 GeV
Lepton η	$\|\eta\| < 2.5$ (e) or 2.4 (μ)
Charge requirements	—
Jet multiplicity	$\geq$2 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets
Missing transverse momentum	—
Dilepton mass	$m_{\ell\ell} > 12$ GeV * and $\|m_{\ell\ell} - m_Z\| > 10$ GeV ‡
Four-lepton mass	$m_{4\ell} > 140$ GeV §

Selection	$2\ell ss$	$2\ell ss + 1\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to bqq$, $H \to WW \to \ell\nu qq$	$t \to b\ell\nu$, $t \to bqq$, $H \to \tau\tau \to \ell\tau_h + \nu$'s
Trigger	Single- or double-lepton triggers	
Lepton multiplicity	Exactly 2 leptons	
Lepton p_T	$p_T > 25$ / 15 GeV	$p_T > 25$ / 15 (e) or 10 GeV (μ)
Lepton η	$\|\eta\| < 2.5$ (e) or 2.4 (μ)	
τ_h multiplicity	No τ_h (loose WP)	$\geq$1 τ_h (loose WP) and $< 2\tau_h$ (medium WP)
τ_h p_T	—	$p_T > 20$ GeV
τ_h η	—	$\|\eta\| < 2.3$
Charge requirements	2 same-sign leptons and charge quality requirements	$\sum_{\ell,\tau_h} q = \pm 1$
Jet multiplicity	$\geq$4 jets	$\geq$3 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	$L_D > 30$ GeV **	
Dilepton mass	$m_{\ell\ell} > 12$ GeV * and $\|m_{ee} - m_Z\| > 10$ GeV **	

Selection	3ℓ	$3\ell + 1\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to b\ell\nu$, $H \to WW \to \ell\nu qq$ $t \to b\ell\nu$, $t \to bqq$, $H \to WW \to \ell\nu\ell\nu$	$t \to b\ell\nu$, $t \to b\ell\nu$, $H \to \tau\tau \to \ell\tau_h + \nu$'s
Trigger	Single-, double- or triple-lepton triggers	
Lepton multiplicity	Exactly 3 leptons	
Lepton p_T	$p_T > 25$ / 15 / 15 GeV	$p_T > 20$ / 10 / 10 GeV
Lepton η	$\|\eta\| < 2.5$ (e) or 2.4 (μ)	
τ_h	No τ_h (loose WP)	≥ 1 τ_h (loose WP)
τ_h p_T	—	$p_T > 20$ GeV
τ_h η	—	$\|\eta\| < 2.3$
Charge requirements	$\sum_{\ell} q = \pm 1$	$\sum_{\ell,\tau_h} q = 0$
Jet multiplicity	$\geq$2 jets	
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	No requirement if $N_j \geq 4$ $L_D > 45$ GeV † $L_D > 30$ GeV otherwise	
Dilepton mass	$m_{\ell\ell} > 12$ GeV * and $\|m_{\ell\ell} - m_Z\| > 10$ GeV ‡	
Four-lepton mass	$m_{4\ell} > 140$ GeV §	—

Selection	$1\ell + 2\tau_h$	$2\ell + 2\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to bqq$, $H \to \tau\tau \to \tau_h\tau_h + \nu$'s	$t \to b\ell\nu$, $t \to b\ell\nu$, $H \to \tau\tau \to \tau_h\tau_h + \nu$'s
Trigger	Single-lepton or lepton+τ_h triggers	Single-, double-lepton triggers
Lepton multiplicity	Exactly 1 lepton	≥ 2 leptons
Lepton p_T	$p_T > 25$ (e) or 20 GeV (μ)	$p_T > 25$ / 15 (e) or 10 GeV (μ)
Lepton η	$\|\eta\| < 2.1$	$\|\eta\| < 2.5$ (e) or 2.4 (μ)
τ_h multiplicity	≥ 2 τ_h (medium WP)	
τ_h p_T	$p_T > 30$ / 20 GeV	$p_T > 20$ GeV
τ_h η	$\|\eta\| < 2.3$	$\|\eta\| < 2.3$
Charge requirements	$\sum_{\tau_h} q = 0$	$\sum_{\ell,\tau_h} q = 0$
Jet multiplicity	$\geq$3 jets	$\geq$2 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	— — —	No requirement if $N_j \geq 4$ $L_D > 45$ GeV † $L_D > 30$ GeV otherwise
Dilepton mass	$m_{\ell\ell} > 12$ GeV *	

MVA variables in γγ (hadronic)

- Photon variables:
  - the $p_T/m_{\gamma\gamma}$ of the two photons;
  - the η of the photons;
  - the azimuthal angle φ of the photons;
  - the photon identification BDT score of the photons;
  - the outcome of the pixel seed veto for the two photons;
  - the $p_T/m_{\gamma\gamma}$ of the diphoton;
  - the rapidity of the diphoton;
- jet variables:
  - the number of jets;
  - the transverse momentum of the four highest p_T jets;
  - the η of the four highest p_T jets;
  - the sum p_T of all the reconstructed jets;
- b-tagged jet variables:
  - the value of the b-discriminant of the three jets with the highest score of the b-discriminant;
  - the value of the b-discriminant of the four highest p_T jets;
- the missing transverse momentum p_T^{miss}.

MVA variables in γγ (leptonic)

- photon variables:
  - the $p_T/m_{\gamma\gamma}$ of the two photons; the p_T is scaled to the diphoton mass to keep the BDT blind to the diphoton invariant mass;
  - the η of the two photons;
  - the photon identification BDT scores of the two photons;
  - the azimuthal angle difference between the two photons $\Delta\phi(\gamma\gamma)$;
  - the outcome of the pixel seed veto for the two photons. The veto requires the absence of a track seed in the pixel detector matching the photon direction, reducing the background due to events where an electron is misidentified as a photon;
- jet variables:
  - the number of jets;
  - the transverse momentum of the three highest p_T jets;
  - the η of the three highest p_T jets;
- b-tagged jet variables:
  - the number of b-tagged jets;
  - the value of the b-discriminant of the two jets with the highest score of the b-discriminant;
- leptonic variables:
  - the transverse momentum of the highest p_T lepton;
  - the η of the lepton of the highest p_T lepton;
- the missing transverse momentum p_T^{miss}.