Measurement of Higgs boson production in association with top quarks with ATLAS

Rencontres du Vietnam 2018, Quy Nhon

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On behalf of the ATLAS collaboration

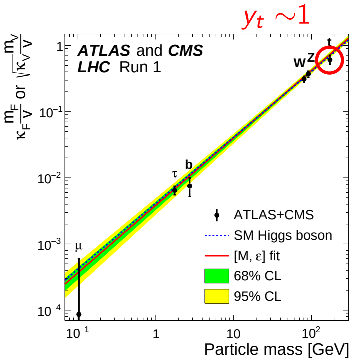
8th August, 2018

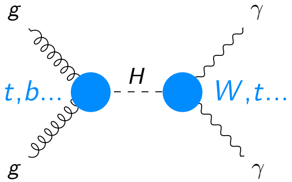
ATLAS EXPERIMENT

Introduction

Higgs Yukawa couplings

- All current measurements of the Higgs boson have been consistent with SM
- Fermions couple with the Higgs boson through *Yukawa interactions*
  - Coupling strength proportional to fermion mass
  - Largest coupling is to the top quark
  - Sensitive to the scale of new physics!
- y_t mainly constrained from loop processes

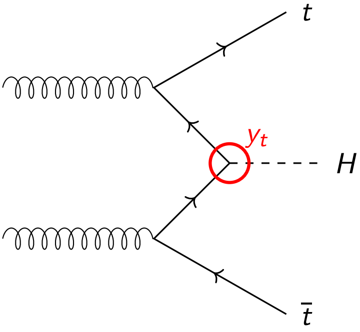




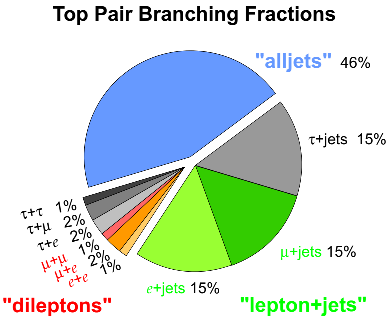
Not model independent, ignores potential BSM contributions

Introduction
$t\bar{t}H$ production

- $t\bar{t}H$: More model independent test of y_t
  - Fourth main Higgs production at LHC
  - Direct measurement of the coupling of Higgs to top quarks
- However, very challenging to measure
  - Small cross section, ∼0.5 pb at 13 TeV
  - Complex final states
  - Large irreducible backgrounds
    - $t\bar{t} + b\bar{b}$, $\mathcal{O}(2)$ magnitudes larger
    - $t\bar{t} + V$, ∼1.5 pb
- Huge efforts to observe $t\bar{t}H$ production during LHC Run 1 and 2



Analysis Strategy



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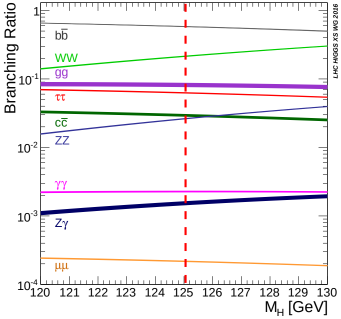


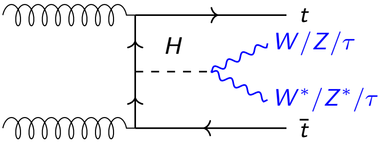
- Wide range of analyses designed to target the various Higgs boson decays
  - Additional considerations to the decay of $t\bar{t}$ pair
  - Final states with many objects: jets, b-jets, e, μ, hadronic τ, photons
  - Huge thanks to the excellent detector performance magnificent effort of ATLAS performance groups

Analysis Strategy

- Four analyses targetting different Higgs decay modes
- Wide range of signal purity and expected yields
- Analysed separately before entering combined analysis

$t\bar{t}H$ multilepton

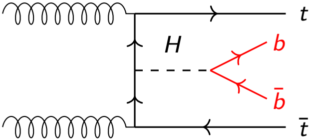
36.1 fb^{-1}, 13 TeV ▸ arXiv



S/B 5–34%

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

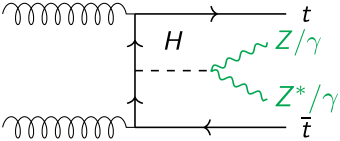
36.1 fb^{-1}, 13 TeV ▸ arXiv



S/B 1.8–5.5%

$t\bar{t}H$ enriched in $H \to \gamma\gamma/4\ell$

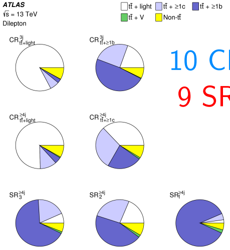
79.8 fb^{-1}, 13 TeV ▸ arXiv



S/B 5–200% ($\gamma\gamma$), 50–500% ($ZZ^* \to 4\ell$)

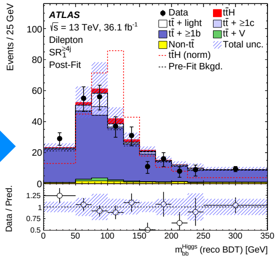
Analysis Strategy
$t\bar{t}H$ $(H \to b\bar{b})$

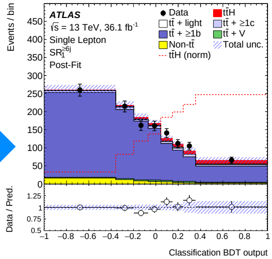
- Benefit from large $H \to b\bar{b}$ BR, selects leptonic top decays
- Large irreducible background from $t\bar{t}+\text{jets}$, especially $t\bar{t}$ +Heavy Flavour
  - Large theory uncertainties, biggest source of systematic uncertainty
- Use of MVA techniques in signal regions to enhance signal sensitivity



10 CRs

9 SRs





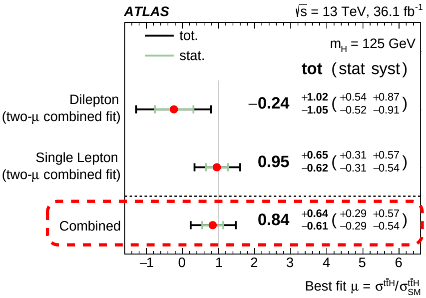
Categorisation
- Use b-tagging of jets and object multiplicities
- Dedicated boosted region targets high p_T top/Higgs

Reconstruction
- Solve object combinatorics to reconstruct final state
- Reco BDT, MEM and Likelihood discriminants

Classification
- BDTs for $t\bar{t}H$ vs $t\bar{t}+\text{jets}$
- Optimised in all SRs
- Reconstruction + event kinematic variables

Analysis Strategy
$t\bar{t}H$ $(H \to b\bar{b})$ Results

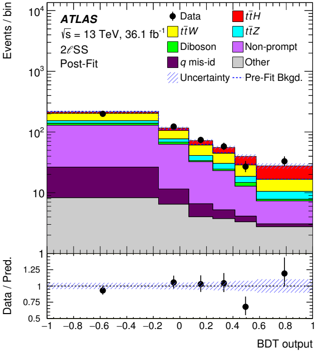
- Binned profile likelihood over all regions
- $t\bar{t}$+$\geq$1b, $t\bar{t}$+$\geq$1c normalisation factors kept free floating
- Significance of 1.4σ (1.6σ expected)
- Systematically limited by modelling of $t\bar{t}$ + HF background

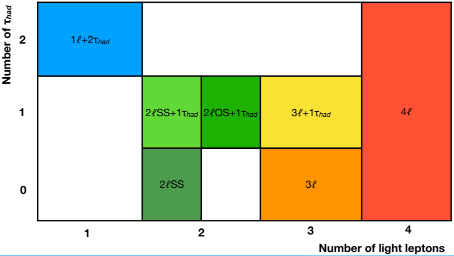


Uncertainty source	$\Delta\mu$	
$t\bar{t}$+$\geq$1b modelling	+0.46	−0.46
Background-model stat. unc.	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modelling	+0.22	−0.05
$t\bar{t}$+$\geq$1c modelling	+0.09	−0.11
JVT, pileup modelling	+0.03	−0.05
Other background modelling	+0.08	−0.08
$t\bar{t}$ + light modelling	+0.06	−0.03
Luminosity	+0.03	−0.02
Light lepton (e, μ) id., isolation, trigger	+0.03	−0.04
Total systematic uncertainty	+0.57	−0.54
$t\bar{t}$+$\geq$1b normalisation	+0.09	−0.10
$t\bar{t}$+$\geq$1c normalisation	+0.02	−0.03
Intrinsic statistical uncertainty	+0.21	−0.20
Total statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61

Analysis Strategy
$t\bar{t}H$ multileptons

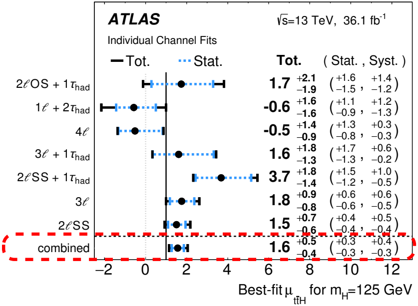
- Target Higgs decays with leptonic final states and leptonic $t\bar{t}$ decays
- Same sign and >3 lepton events reduce $t\bar{t}$ background
  - Requirements on (b-)jet multiplicities
  - Events categorised by number of leptons & hadronic taus
  - Wide range of yields and S/B purity
  - Seven final states in total





- Object level BDTs used to reduce non-prompt leptons and charge mis-ID
- Enhance separation from $t\bar{t}$, $t\bar{t}V$ with BDTs
  - Event count in $3\ell 1\tau_{had}$ and $4l$

Analysis Strategy
$t\bar{t}H$ multileptons Results



Channel	Significance Obs.	Significance Exp.
$2\ell OS + 1\tau_{had}$	0.9σ	0.5σ
$1\ell + 2\tau_{had}$	-	0.6σ
4ℓ	-	0.8σ
$3\ell + 1\tau_{had}$	1.3σ	0.9σ
$2\ell SS + 1\tau_{had}$	3.4σ	1.1σ
3ℓ	2.4σ	1.5σ
$2\ell SS$	2.6σ	1.9σ
Combined	4.1σ	2.8σ

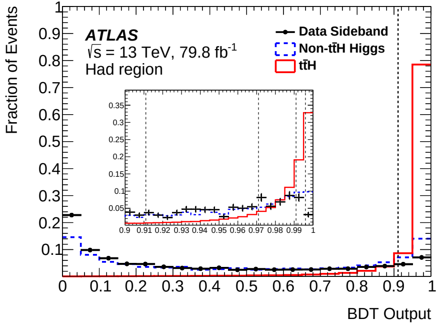
- Binned profile likelihood across all regions
- Observed significance of 4.1σ for $t\bar{t}H$ production (2.8σ exp)
- Additional cut based cross check analysis performed
  - Consistent results with the MVA based approach
  - 15% poorer sensitivity
- Leading systematics from $t\bar{t}H$ and $t\bar{t}V$ modelling, non-prompt lepton estimates and jet energy scale/resolution

Analysis Strategy
$t\bar{t}H\,(\gamma\gamma)$

79.8 fb^{-1}!!!

- Small rate but very signal enriched regions with a continuous background
- Reconstruct Higgs as a narrow peak, use side bands to estimate background
  - Main background from non-resonant $\gamma\gamma$ and non-$t\bar{t}H$ production

- Categorise events by leptonic ($>1\ell$) and hadronic (0ℓ) $t\bar{t}$ decays
- Train BDTs to separate $t\bar{t}H$ from background in lep and had
  - Jet/lepton 4-vector info
  - Photon observables
  - E_T^{miss} and b-tagging
- Cut on BDT distributions to define signal rich regions
  - Seven regions in total



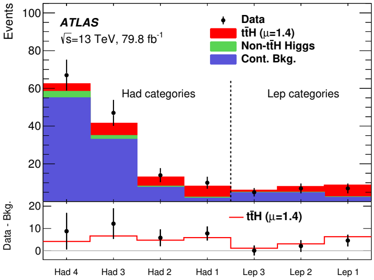
50% improvement in sensitivity

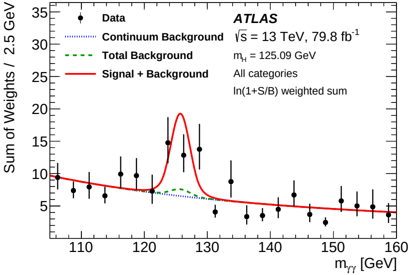
2016 analysis

Analysis Strategy
$t\bar{t}H\,(\gamma\gamma)$ Results

79.8 fb^{-1}!!!

- Unbinned maximum likelihood fit over $m_{\gamma\gamma}$ in range 105 – 160 GeV
  - Non-$t\bar{t}H$ production fixed to SM prediction
  - Function for $\gamma\gamma$ background derived in each regions
    - Leptonic regions: simulation
    - Hadronic regions: data driven from control region
- Observed significance of 4.1σ for $t\bar{t}H$ production (3.7σ expected)
  - Measured signal strength $\mu = 1.39^{+0.48}_{-0.42} = 1.39^{+0.42}_{-0.36}(\text{stat.})^{+0.23}_{-0.17}(\text{syst.})$
- Currently statistically limited ($\sim$29% stat uncertainty)



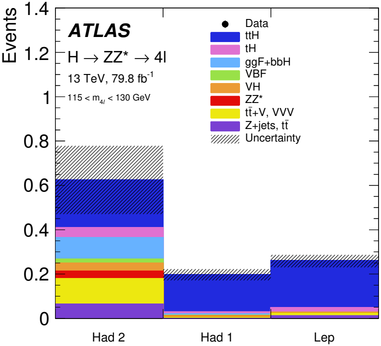


Analysis Strategy
$t\bar{t}H$ (4ℓ)

79.8 fb^{-1}!!!

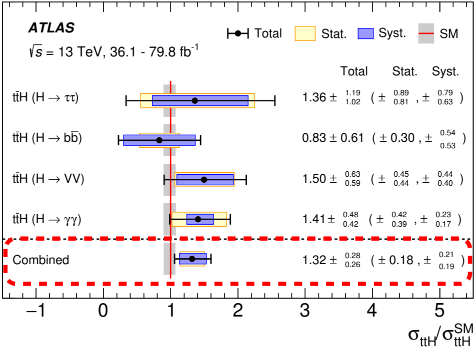
- Extremely low rate but very high signal to background ratio (up to 500%!)
- Look at 4ℓ inv-mass window 115–130 GeV
- Categorise events by $t\bar{t}$ decay: leptonic (1 additional ℓ) and hadronic (0 additional ℓ)
  - Further split hadronic into two bins with BDT to enhance $t\bar{t}H$ purity
- No observed events
  - Fewer than one expected event
- Expected significance of 1.2σ
- Very statistically limited

Region	Expected $t\bar{t}H$	Expected Non-$t\bar{t}H$ Higgs	Expected Other bkg	Observed
Had 2	0.169(31)	0.021(7)	0.008(8)	0
Had 1	0.216(32)	0.20(9)	0.22(12)	0
Lep	0.212(31)	0.0256(23)	0.015(13)	0



Combined Result

- Combination of all four analyses performed using profile likelihood method



Fit details

- Negligible overlap between events in each analysis
- Non-$t\bar{t}H$ Higgs production fixed to SM prediction
- Correlation scheme studied in detail

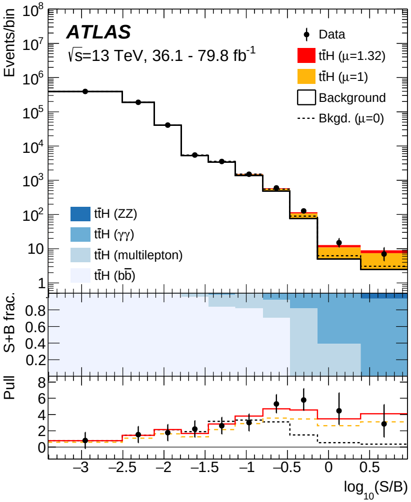
- Observation of $t\bar{t}H$ production at 13 TeV. 5.8σ observed (4.9σ expected)
- Measured $t\bar{t}H$ cross section at $\sqrt{s} = 13$ TeV:

$$\sigma_{t\bar{t}H} = 670 \pm 90(\text{stat})^{+110}_{-100}(\text{syst})\ \text{fb}^{-1}$$

- Cross section 1.32× SM prediction, compatible with SM at around 1σ level

arXiv

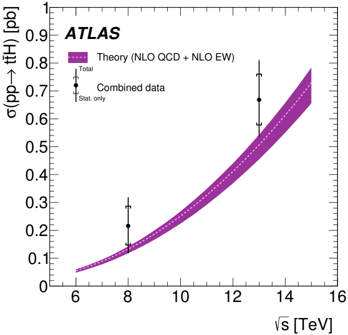
Combined Result



- Some channels still very much limited by statistics
- Modelling uncertainties dominate the systematic uncertainties

Uncertainty source	$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ [%]
Theory uncertainties (modelling)	11.9
$t\bar{t}$ + heavy flavour	9.9
$t\bar{t}H$	6.0
Non-ttH Higgs boson production modes	1.5
Other background processes	2.2
Experimental uncertainties	9.3
Fake leptons	5.2
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	4.9
Electrons, photons	3.2
Luminosity	3.0
τ-lepton	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4

Combination with Run 1



- Combine the 13 TeV result with the ATLAS Run 1 result ▸ EPJC 76 (2016) 6
  - Additional 4.5 fb^{-1} 7 TeV and 20.3 fb^{-1} 8 TeV data
- 6.3σ observed significance, 5.1σ expected!

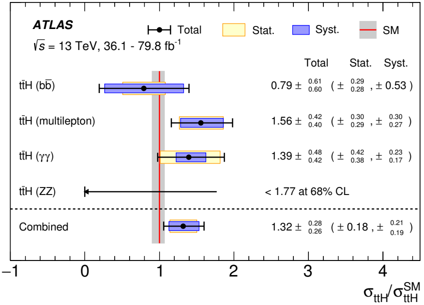
Analysis	Integrated luminosity $[\text{fb}^{-1}]$	$t\bar{t}H$ cross section [fb]	Obs. sign.	Exp. sign.
$H \to \gamma\gamma$	79.8	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)	$4.1\ \sigma$	$3.7\ \sigma$
$H \to$ multilepton	36.1	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)	$4.1\ \sigma$	$2.8\ \sigma$
$H \to b\bar{b}$	36.1	$400\ ^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)	$1.4\ \sigma$	$1.6\ \sigma$
$H \to ZZ^* \to 4\ell$	79.8	<900 (68% CL)	$0\ \sigma$	$1.2\ \sigma$
Combined (13 TeV)	36.1−79.8	670 ± 90 (stat.) $^{+110}_{-100}$ (syst.)	$5.8\ \sigma$	$4.9\ \sigma$
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1−79.8	–	$6.3\ \sigma$	$5.1\ \sigma$

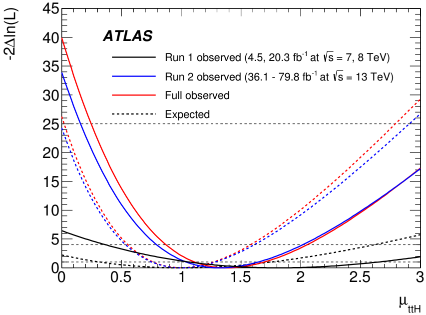
Conclusion

- Search for $t\bar{t}H$ production performed at 13 TeV using 36.1 – 79.8 fb^{-1} data
- Combination of several challenging analyses
  - Extensive use of multivariate techniques to enhance sensitivity
  - Large systematic uncertainties on modelling
  - Some channels statistically limited, will only become more sensitive!
- ATLAS observation of $t\bar{t}H$ with a significance of 6.3σ (5.1σ exp)
  - Direct observation of top Yukawa coupling
  - Measured $\sigma_{t\bar{t}H} = 670 \pm 90(\mathrm{stat})^{+110}_{-100}(\mathrm{syst})$ fb^{-1} at 13 TeV
  - Consistent with SM prediction $\sigma_{t\bar{t}H} = 507^{+35}_{-50}$ fb^{-1}

Backup

Combination

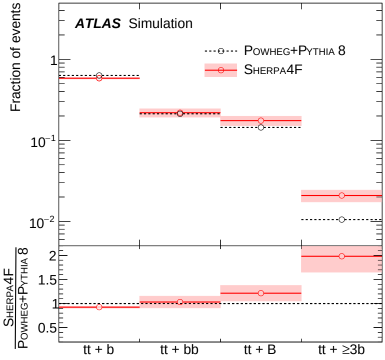




$t\bar{t}H$ $(H \rightarrow b\bar{b})$ - $t\bar{t}$ Background Model

Modelling of $t\bar{t}$ is crucial to the analysis, $t\bar{t} + \mathrm{HF}$ has large theory uncertainty

- Split into $t\bar{t} + \mathrm{light}$, $t\bar{t}+\geq 1c$, $t\bar{t}+\geq 1b$
  - Further split $t\bar{t}+\geq 1b$ by number of additional b-hadrons in jets
- Nominal $t\bar{t}$ sample uses 5FS prediction
  - Use dedicated Sherpa 4FS $t\bar{t} + b\bar{b}$ prediction to improve modelling
    - Both additional b-quarks to NLO precision in QCD
    - Takes b-quark mass into account
  - Reweight relative $t\bar{t}+\geq 1b$ subcomponents to 4FS values

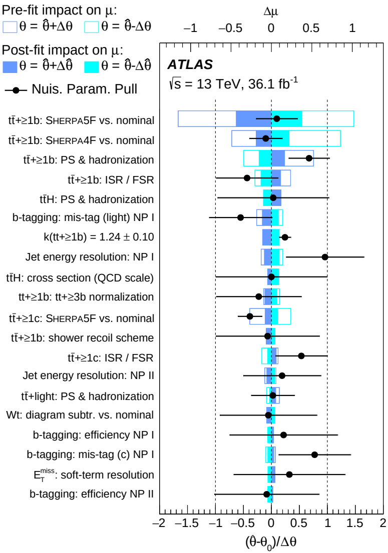


$t\bar{t}H$ $(H \to b\bar{b})$ - $t\bar{t}$ Systematic Model

$t\bar{t}$ modelling is dominant contribution to total systematic uncertainty

Systematic source	Description	$t\bar{t}$ categories
$t\bar{t}$ cross-section	Up or down by 6%	All, correlated
$k(t\bar{t}+\geq 1c)$	Free-floating $t\bar{t}+\geq 1c$ normalization	$t\bar{t}+\geq 1c$
$k(t\bar{t}+\geq 1b)$	Free-floating $t\bar{t}+\geq 1b$ normalization	$t\bar{t}+\geq 1b$
SHERPA5F vs. nominal	Related to the choice of NLO event generator	All, uncorrelated
PS & hadronization	POWHEG+HERWIG 7 vs. POWHEG+PYTHIA 8	All, uncorrelated
ISR / FSR	Variations of μ_{R}, μ_{F}, h_{damp} and A14 Var3c parameters	All, uncorrelated
$t\bar{t}+\geq 1c$ ME vs. inclusive	MG5_aMC@NLO+HERWIG++: ME prediction (3F) vs. incl. (5F)	$t\bar{t}+\geq 1c$
$t\bar{t}+\geq 1b$ SHERPA4F vs. nominal	Comparison of $t\bar{t}+b\bar{b}$ NLO (4F) vs. POWHEG+PYTHIA 8 (5F)	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ renorm. scale	Up or down by a factor of two	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ resumm. scale	Vary μ_{Q} from $H_{\mathrm{T}}/2$ to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ global scales	Set μ_{Q}, μ_{R}, and μ_{F} to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ shower recoil scheme	Alternative model scheme	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ PDF (MSTW)	MSTW vs. CT10	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ PDF (NNPDF)	NNPDF vs. CT10	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ UE	Alternative set of tuned parameters for the underlying event	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 3b$ normalization	Up or down by 50%	$t\bar{t}+\geq 1b$

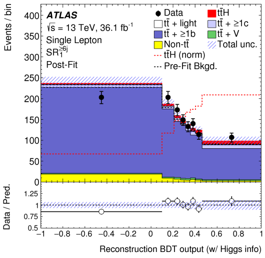
$t\bar{t}H$ $(H \to b\bar{b})$ - Impact of Systematic Uncertainties



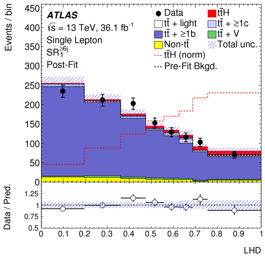
- Analysis is currently systematically limited
- Largest uncertainties from $t\bar{t} + \mathrm{HF}$ modelling
- Also notable impact:
  - Limited MC stats.
  - Flavour tagging
  - Jet energy scale and resolution
- Large number of constrained two-point systematics

$t\bar{t}H\ (H \to b\bar{b})$ - Reconstruction Methods

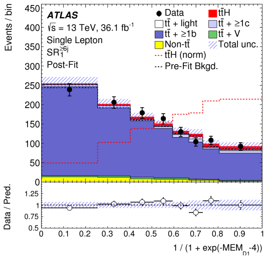
Reco BDT



LHD



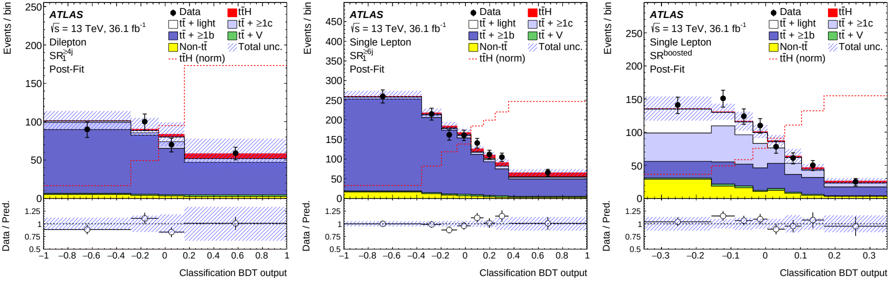
MEM



Reco BDT	Exploits correlations within each combination
Reco BDT	Provides jet assignments based on $t\bar{t}H\ (H \to b\bar{b})$
LHD	Combines all combinations together into one discriminant
LHD+MEM	Calculate both signal and background likelihoods
MEM	Calculates discriminant at parton level using 4-vectors

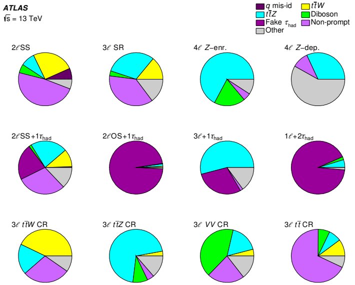
$t\bar{t}H$ $(H \to b\bar{b})$- Final Discriminant

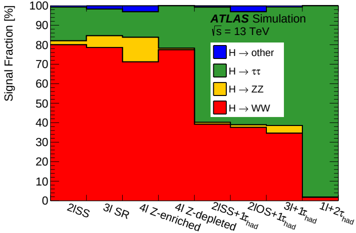
- Looking at three signal regions post fit
  - $t\bar{t}H$ shown for extracted signal strength $\mu = 0.84^{+0.64}_{-0.61}$
  - Showing two most signal enriched regions and boosted signal region
- See good post-fit agreement between data and simulation in all regions



$t\bar{t}H$ ML - Regions

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)
1ℓ+$2\tau_{\text{had}}$	One tight light lepton with $p_{\text{T}} > 27$ GeV Two medium τ_{had} candidates of opposite charge, at least one being tight $N_{\text{jets}} \geq 3$
2ℓSS+$1\tau_{\text{had}}$	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
2ℓOS+$1\tau_{\text{had}}$	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 $N_{\text{jets}} \geq 3$
3ℓ+$1\tau_{\text{had}}$	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



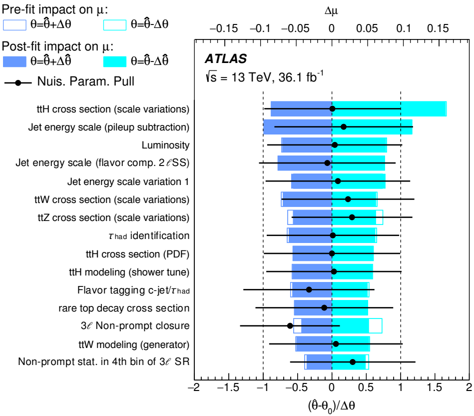


$t\bar{t}H$ ML - BDTs

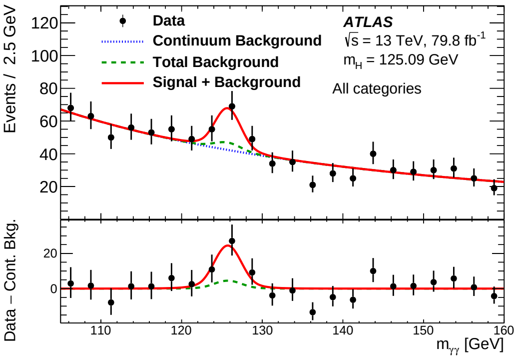
	2ℓSS	3ℓ	4ℓ	1ℓ+$2\tau_{\text{had}}$	2ℓSS+$1\tau_{\text{had}}$	2ℓOS+$1\tau_{\text{had}}$	3ℓ+$1\tau_{\text{had}}$
Light lepton	2T*	1L*, 2T*	2L, 2T	1T	2T*	$2\text{L}^{\dagger}$	$1\text{L}^{\dagger}$, 2T
τ_{had}	0M	0M	–	1T, 1M	1M	1M	1M
N_{jets}, $N_{b\text{-jets}}$	$\geq 4, = 1, 2$	$\geq 2, \geq 1$	$\geq 2, \geq 1$	$\geq 3, \geq 1$	$\geq 4, \geq 1$	$\geq 3, \geq 1$	$\geq 2, \geq 1$

$t\bar{t}H$ ML - Systematics

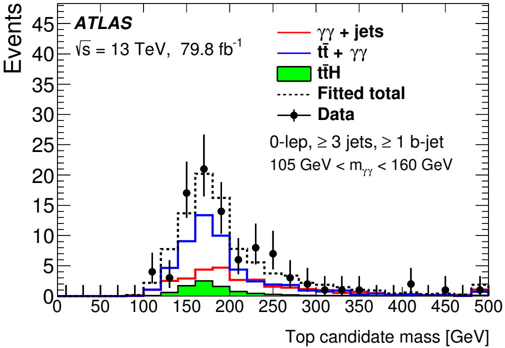
Uncertainty Source	$\Delta\mu$	
$t\bar{t}H$ modeling (cross section)	+0.20	−0.09
Jet energy scale and resolution	+0.18	−0.15
Non-prompt light-lepton estimates	+0.15	−0.13
Jet flavor tagging and τ_{had} identification	+0.11	−0.09
$t\bar{t}W$ modeling	+0.10	−0.09
$t\bar{t}Z$ modeling	+0.08	−0.07
Other background modeling	+0.08	−0.07
Luminosity	+0.08	−0.06
$t\bar{t}H$ modeling (acceptance)	+0.08	−0.04
Fake τ_{had} estimates	+0.07	−0.07
Other experimental uncertainties	+0.05	−0.04
Simulation sample size	+0.04	−0.04
Charge misassignment	+0.01	−0.01
Total systematic uncertainty	+0.39	−0.30



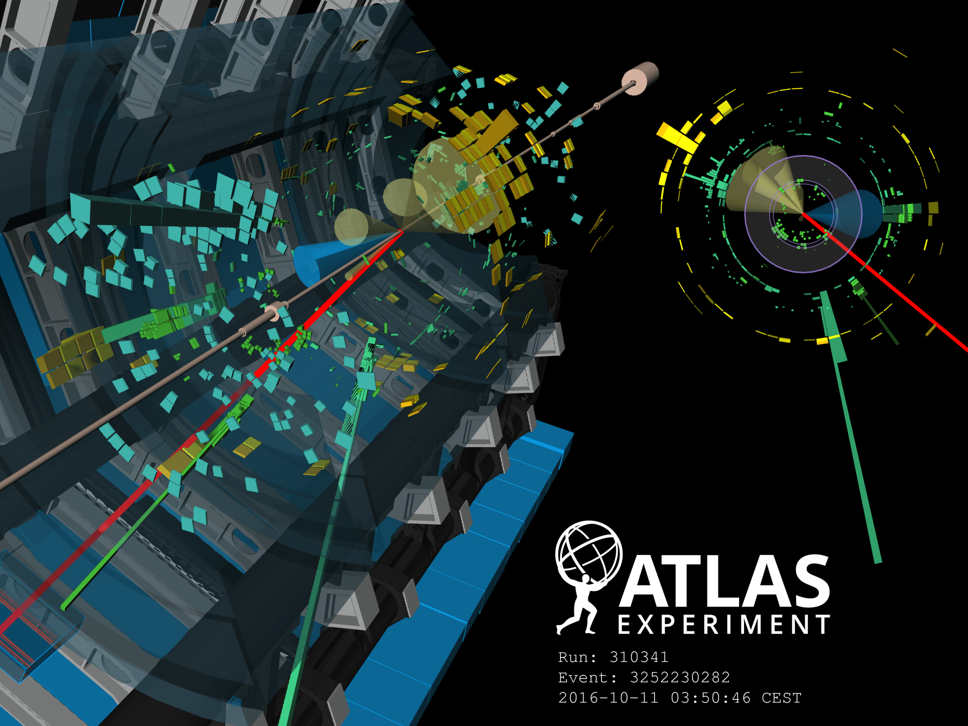
$t\bar{t}H\,(H \to \gamma\gamma)$ - Unweighted $m_{\gamma\gamma}$



$t\bar{t}H\,(H \rightarrow \gamma\gamma)$ - Unweighted $m_{\gamma\gamma}$



- BDT trained to select three jets form hadronic top
- Does not enter the analysis
- Top mass reconstructed in bins with highest S/B
- Excess in events around top mass consistent with $t\bar{t}H$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