

Evidence for Higgs boson production in association with a $t\overline{t}$ pair

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Introduction Higgs production at the LHC



- Higgs boson discovery in 2012 by ATLAS & CMS
- Is it "the expected" Higgs boson? \rightarrow potential door to BSM
- $t\bar{t}H$: special production process \rightarrow low XS \rightarrow not yet observed by ATLAS



Introduction The top Yukawa coupling



- Yukawa coupling $y_f \propto m_f$
- For top quark: y_t ≈ 1
 ⇒ sensitive to new physics





• *t*t*H* allows direct measurement

- gg fusion and $H \rightarrow \gamma \gamma$ decay
 - \Rightarrow only indirect measurement
 - Jannik Geisen, CIPANP 2018

Introduction Top and Higgs decays



- $\sigma_{SM}^{ttH} = 507^{+35}_{-50}$ fb \rightarrow only $\approx 1\%$ of Higgs produced at the LHC \Rightarrow Upside: additional $t\bar{t}$ pair improves signal purity significantly
- Different top & Higgs decays → many different event topologies
 ⇒ Four main analyses in ATLAS, studying different Higgs decays:
 - $\Rightarrow H \rightarrow b\bar{b}, H \rightarrow ML \text{ (multi-leptons)}, H \rightarrow ZZ^* \rightarrow 4l \text{ (resonant)}, H \rightarrow \gamma\gamma$

Higgs branching ratios:





$t\bar{t}H(H \rightarrow b\bar{b})$ Phys. Rev. D 97, 072016 (2018)

$t\bar{t}H(H ightarrow b\bar{b})$ Details and challenges



- Complex final state \rightarrow semileptonic/dileptonic $t\overline{t}$ decay (allhad only Run I) \Rightarrow 4 or 6 jets & 4 *b*-jets at LO!
- Systematic impact of objects: jets, b-tagging, leptons, MET
- Largest background: $t\bar{t}$ + jets (light flavour, $c\bar{c}$, $b\bar{b}$ = "irreducible") $\Rightarrow t\bar{t} + b\bar{b}$ cross-section \approx 30 times higher than signal
 - \Rightarrow Analysis depends on discriminating $t\bar{t}H(H \rightarrow b\bar{b})$ from $t\bar{t} + b\bar{b}$



$t \overline{t} H(H o b \overline{b})$ Analysis strategy



- Split channel using $N_{\text{jets}} \& N_{b-\text{jets}}$ (different *b*-tagging working points) \Rightarrow Regions enriched in $t\overline{t} + \text{If}/c\overline{c}/b\overline{b}/\text{Higgs}$
- High values of N_{jets} & N_{b−jets}: phase-space closer to signal region (SR)
 ⇒ Other regions are control regions (CR): constrain & estimate background



Single lepton regions with $N_{jets} \ge 6$ Highest signal purity: select 4 (very) tight *b*-tagged jets \rightarrow "SR1"

$t \bar{t} H (H ightarrow b ar{b})$ MVA and fit



- Final state reconstructed by BDT \Rightarrow finds $b\bar{b}$ from Higgs
- Then fed into classification BDT \Rightarrow discriminate $t\bar{t}H(H \rightarrow b\bar{b})$ vs. $t\bar{t} + b\bar{b}$





$t\bar{t}H(H ightarrow b\bar{b})$ Results



- Parameter of interest: signal strength $\mu = \sigma^{t\bar{t}H}/\sigma^{t\bar{t}H}_{\rm SM}$
- Systematically limited by MC modelling + background modelling stats \Rightarrow Estimating $t\bar{t} + b\bar{b}$ by comparing different MC generators
- Also: *b*-tagging, JES/JER
- No significant gain from more data \rightarrow need to improve modelling





$t\overline{t}H(H \rightarrow ML)$ Phys. Rev. D 97, 072003 (2018)

$t\bar{t}H(H \rightarrow \mathbf{ML})$ Details and challenges



- Includes $H \rightarrow WW^*/ZZ^*/\tau\tau$; complex final state \Rightarrow 1-4 leptons, 0-2 taus
- Split into 7 channels using $N_{
 m leptons}$, $N_{ au_{
 m had}}$, lepton charge
- Many different event topologies \Rightarrow optimisation on many objects
- Systematic impact: leptons (prompt & non-prompt/fakes), MET, b-tagging, jets
- Veto $t\bar{t}H(H \rightarrow \mathsf{ZZ}^* \rightarrow \mathsf{4I}) \rightarrow \mathsf{individual}$ analysis





Two main background components:

- Prompt leptons \rightarrow estimate via MC: $t\overline{t}W, t\overline{t}Z$, Diboson
- Fake τ_{had} ; fake & non-prompt (light) leptons; charge mis-ID (electrons) \Rightarrow data-driven estimate









$t\overline{t}H(H ightarrow \mathbf{ML})$ MVA and fit



Two MVA stages:

- Object level BDTs \rightarrow remove bad leptons
 - Non-prompt leptons via isolation-like BDT
 - Charge mis-ID via BDT
- Event level MVA \rightarrow discriminate $t\bar{t}H(H \rightarrow ML)$ vs. backgrounds
 - Combine multiple BDTs with multi-dimensional binning



$t\overline{t}H(H ightarrow \mathbf{ML})$ Results



- 2 same-sign (light) leptons "2ISS" and 3 (light) leptons "3I" \Rightarrow Most sensitive channels
- Dominant systematics: signal & background modelling, JES & JER, non-prompt light-lepton estimate, flavour-tagging, $\tau_{\rm had}\text{-ID}$
- Visible signal above background after combining channels \Rightarrow Significance: 4.1 σ observed, 2.8 σ expected





$t\overline{t}H(H \longrightarrow ZZ^* \longrightarrow 4I)$

 $t\bar{t}H(H \rightarrow \mathbf{ZZ}^* \rightarrow 4\mathbf{I})$

Overview and results



- Part of $H \rightarrow ZZ^* \rightarrow 4I$ analysis; inclusive $H \rightarrow ZZ^* \rightarrow 4I$ selection
- Get $t\bar{t}H$ via $N_{\rm jets},~N_{bm jets}
 ightarrow$ very pure channel: S/B pprox 125-300%
- **BUT:** very low statistics $\sigma \times BR = 0.507 \text{ pb} \times 0.0001251$
- No data event found in signal region \rightarrow more data needed \rightarrow set limits: \Rightarrow σ \times BR < 1.9 (7.1) times SM @ 68% (95%) CL





$t\overline{t}H(H \rightarrow \gamma\gamma)$

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

Overview and results



- Part of $H \rightarrow \gamma \gamma$ analysis, inclusive $H \rightarrow \gamma \gamma$ selection
- Again channel with low statistics: $\sigma \times BR = 0.507 \text{ pb} \times 0.00227$
- Get $t\bar{t}H$ via $N_{
 m jets},~N_{bm jets}
 ightarrow$ hadronic and leptonic categories
- Use excellent resolution on $m_{\gamma\gamma}$ to discriminate signal vs. background
- $t\bar{t}H + tH$ result: $\mu_{top} = 0.5 \ ^{+0.6}_{-0.5}(\text{stat}) \pm 0.1(\text{syst}) \rightarrow$ limited by statistics





tTH combination Phys. Rev. D 97, 072003 (2018)

$t\bar{t}H$ combination

Final combined results





- Evidence for $t\overline{t}H$ in ATLAS
- Measured cross-sections compatible with SM

Summary

 $t\bar{t}H$ searches in ATLAS



What you can take away

- $t\bar{t}H$ search is very challenging
- Individual analyses have their own challenges and limitations $\Rightarrow t\bar{t}H(H \rightarrow ML)$ highest sensitivity on μ
- ATLAS found evidence for $t\overline{t}H \rightarrow$ compatible with SM
- Next steps:
 - Current results use 2015 + 2016 data (36.1 fb⁻¹) \rightarrow include more data \Rightarrow 79.7 fb⁻¹ when including 2017 data $\Rightarrow \approx 140 \text{ fb}^{-1}$ expected with full Run II
 - Develop improved analyses techniques to decrease systematics on couplings

Channel	Best-fit μ		Significance	
	Observed	Expected	Observed	Expected
Multilepton	$1.6 \ ^{+0.5}_{-0.4}$	$1.0 \ ^{+0.4}_{-0.4}$	4.1σ	2.8σ
$H \to b \bar{b}$	$0.8 \ ^{+0.6}_{-0.6}$	$1.0 \ ^{+0.6}_{-0.6}$	1.4σ	1.6σ
$H\to\gamma\gamma$	$0.6 \ ^{+0.7}_{-0.6}$	$1.0 \ ^{+0.8}_{-0.6}$	0.9σ	1.7σ
$H\to 4\ell$	< 1.9	$1.0 \ ^{+3.2}_{-1.0}$	_	0.6σ
Combined	$1.2 \ ^{+0.3}_{-0.3}$	$1.0 \ ^{+0.3}_{-0.3}$	4.2σ	3.8σ



Thank you for your attention!



Backup

$t\bar{t}H(H ightarrow b\bar{b})$ Systematics ranking





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

 $t\bar{t}H(H \rightarrow b\bar{b})$ S/B and S/\sqrt{B}





• S/B > 5% and $S/\sqrt{B} \approx 2$ in purest signal region!

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





 $t\bar{t}H(H \rightarrow b\bar{b})$ **Dilepton regions**









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

$t\bar{t}H$ combination Uncertainty contributions



Uncertainty Source		$\Delta \mu$	
$t\bar{t}$ modeling in $H \to b\bar{b}$ analysis	+0.15	-0.14	
$t\bar{t}H$ modeling (cross section)	+0.13	-0.06	
Non-prompt light-lepton and fake τ_{had} estimates	+0.09	-0.09	
Simulation statistics	+0.08	-0.08	
Jet energy scale and resolution	+0.08	-0.07	
$t\bar{t}V$ modeling	+0.07	-0.07	
$t\bar{t}H$ modeling (acceptance)	+0.07	-0.04	
Other non-Higgs boson backgrounds		-0.05	
Other experimental uncertainties		-0.05	
Luminosity	+0.05	-0.04	
Jet flavor tagging	+0.03	-0.02	
Modeling of other Higgs boson production modes		-0.01	
Total systematic uncertainty		-0.23	
Statistical uncertainty		-0.19	
Total uncertainty	+0.34	-0.30	

• $t\bar{t}$ modelling in $t\bar{t}H(H \rightarrow b\bar{b}) =$ leading uncertainty in full combination!

$t\bar{t}H$ combination $t\bar{t}H(H \rightarrow b\bar{b})$ difference ATLAS vs CMS



ATLAS



CMS

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