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Measurement of associated production of a heavy boson (Z/W/Higgs) with two top quarks

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on behalf of the ATLAS collaboration

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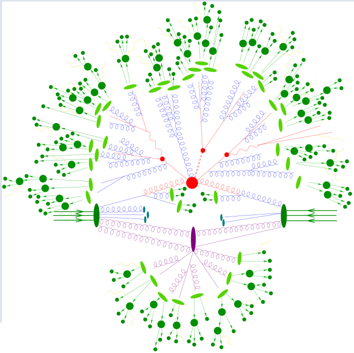
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

BMBF-Forschungsschwerpunkt
ATLAS-EXPERIMENT
Physik bei höchsten Energien mit dem ATLAS-Experiment am LHC
FSP 103
ATLAS

Most recent ATLAS results

I will present cross-section measurements at $\sqrt{s} = 13$ TeV and comparisons to MC predictions of:

1. $t\bar{t}Z$ & $t\bar{t}W$
    - same-sign/opposite-sign dileptons (e,μ)
    - trilepton channel
    - tetralepton channel
2. $t\bar{t}H$
    - $t\bar{t}H(H \rightarrow b\bar{b})$
    - $t\bar{t}H$(multi-leptons $\equiv$ ML)
    - $t\bar{t}H(H \rightarrow \gamma\gamma)$
    - $t\bar{t}H(H \rightarrow ZZ^* \rightarrow 4l)$
    - Combination



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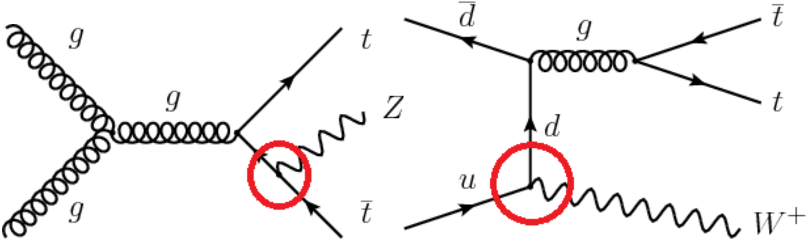
$t\bar{t}Z$ and $t\bar{t}W$

Phys. Rev. D **99**, 072009 (2019)



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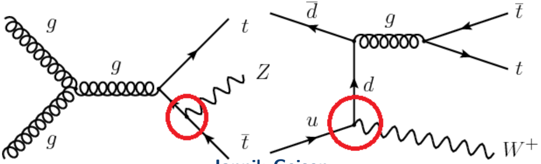
Why do we search for $t\bar{t}Z$ and $t\bar{t}W$?

- Rare processes with small cross-section → important for SM validation
- Direct probe of neutral current weak couplings at t-Z vertex
  - Sensitive to third component of weak isospin
  - Couplings may be modified in certain BSM scenarios
  - Deviations from SM can be parametrised in model-independent way (EFT)
  - No deviations → XS can be used to set constraints on couplings
- Background in searches such as:
  - Final states containing multiple leptons and b-quarks
  - $t\bar{t}H$

⇒ Important to measure its potential contribution as precisely as possible



- MG5_aMC@NLO+Pythia8 predicts at NLO (+QCD & EW corr.): $\sigma_{t\bar{t}Z}$ = **0.88** pb (±12%); $\sigma_{t\bar{t}W}$ = **0.60** pb (±12%)
- Search performed in multiple channels
  - Depending on lepton number, flavour, sign ($t\bar{t}W^+$ more likely than $t\bar{t}W^-$)
- Main backgrounds: Z+jets, $t\bar{t}$, non-prompt/mis-id leptons, WZ, ZZ

Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W$	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{\pm}\nu$	SS dilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{\pm}\nu$	Trilepton
$t\bar{t}Z$	$(q\bar{q}b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	OS dilepton
	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	Trilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{+}\ell^{-}$	Tetralepton

- Regions further split based on number of jets & b-jets
- b-tagging discr. at 77% W.P.

- MVA to distinguish prompt leptons from had. decays in HF jet ($t\bar{t}W$)
  - Use info from tracks around lep.
- MVA to discriminate electrons with misidentified charge (SS dilepton)
  - $e^{\pm}$ track & cluster properties
- Depending on region, apply cuts: $H_T, E_T^{\text{miss}}, p_T^{\text{lep}^1}, p_T^{\text{lep}^2}, |m_{ll} - m_Z|$

Event selection & strategy for $t\bar{t}Z$

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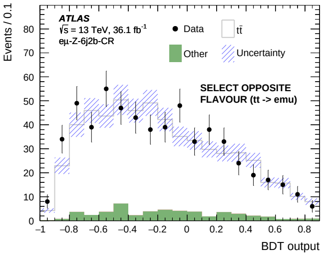
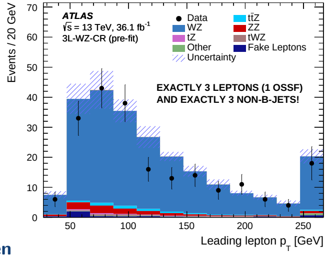
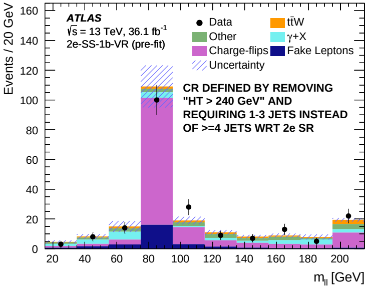
Channel	Backgrounds	Estimation strategy
OS dilepton Use BDT to discriminate signal from background	Z+jets	Z+0 heavy flavour (HF) from MC, Z+1(+2) HF from fit to data in CR;
	$t\bar{t}$	dedicated CR (select $e\mu$)
Trilepton four signal regions (SR) incl. off-shell Z^*/γ^*	WZ, ZZ	CR to estimate norm. in data;
	tZ, tWZ	estimated from MC;
	Z+jets with fake lep	estimated from MC
Tetralepton select 2 OS lep pairs, at least 1 same flavour (SF)	Fake leptons	estimated in MC, corrected by SF determined from two CR;
	ZZ	CR to estimate norm. in data

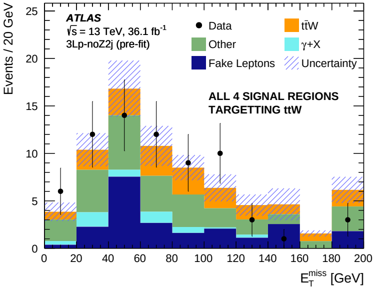




Event selection & strategy for $t\bar{t}W$

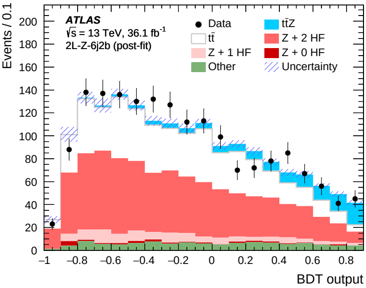
Channel	Backgrounds	Estimation strategy
SS dilepton Split regions based on charge (W preferably positive, background charge symmetric)	Fake leptons	CR + matrix method
	Charge-flip (significant in ee regions)	dedicated CR and validation region
Trilepton Veto on Z mass for OSSF lepton pair	Fake leptons	CR + matrix method
regions split by total charge	other SM processes with 3 prompt leptons	estimated from MC

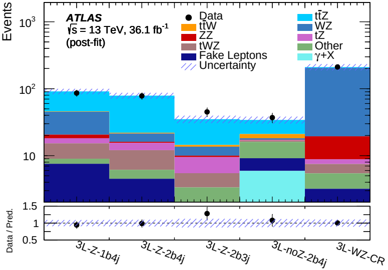




- Simultaneous profile-likelihood fit to all SR and CR
  - OS dilepton: fit BDT distribution
  - Other channels: fit event yields
- Alternative fit configurations:
  - $t\bar{t}Z$: 1) OS dilepton alone; 2) trilepton alone; 3) tetralepton alone
  - $t\bar{t}W$ channels alone

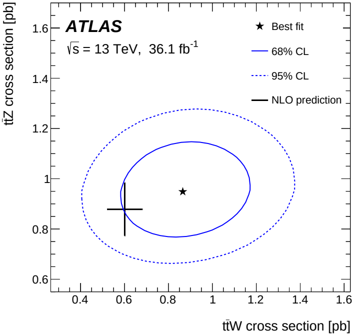
$\Rightarrow$ Individual fit results compatible with combined result within 1σ





$$\mu = \sigma_{\text{measured}} / \sigma_{\text{SM}}$$

Fit configuration	$\mu_{t\bar{t}Z}$	$\mu_{t\bar{t}W}$
Combined	1.08 ± 0.14	1.44 ± 0.32
2ℓ-OS	0.73 ± 0.28	–
3ℓ $t\bar{t}Z$	1.08 ± 0.18	–
2ℓ-SS and 3ℓ $t\bar{t}W$	–	1.41 ± 0.33
4ℓ	1.21 ± 0.29	–



- Use SM prediction to translate μ values:
  - $\sigma_{t\bar{t}Z} = 0.95 \pm 0.08$ (stat) $\pm\, 0.10$ (syst) pb $= 0.95 \pm 0.13$ pb
  - $\sigma_{t\bar{t}W} = 0.87 \pm 0.13$ (stat) $\pm\, 0.14$ (syst) pb $= 0.87 \pm 0.19$ pb
- Results compatible with SM expectation
  - $t\bar{t}Z$ well over 5σ significance; $t\bar{t}W$ 4.3σ obs. (3.4σ exp.) $\rightarrow$ evidence

Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.9%	4.5%
Simulated sample statistics	2.0%	5.3%
Data-driven background statistics	2.5%	6.3%
JES/JER	1.9%	4.1%
Flavor tagging	4.2%	3.7%
Other object-related	3.7%	2.5%
Data-driven background normalization	3.2%	3.9%
Modeling of backgrounds from simulation	5.3%	2.6%
Background cross sections	2.3%	4.9%
Fake leptons and charge misID	1.8%	5.7%
$t\bar{t}Z$ modeling	4.9%	0.7%
$t\bar{t}W$ modeling	0.3%	8.5%
Total systematic	10%	16%
Statistical	8.4%	15%
Total	13%	22%

- Systematics implemented as NP constrained by Gaussian PDFs
- Most NP found not sign. constrained/pulled by fit

- Most significant systematics:
  - Fake leptons, esp. in $t\bar{t}W$ from using the matrix method
  - Charge-flip probability through ee events with $m_{ll} \approx m_Z$
- Normalisation correction factors for WZ, ZZ, Z+1HF, Z+2HF compatible with 1
- Syst. & stat. uncertainties for both processes roughly in same order
  - Most dominant in $t\bar{t}Z$: bkgd modelling; signal modelling
  - Most dominant in $t\bar{t}W$: signal modelling; limited statistics in data CR & MC samples; fake lepton & charge-flip bkgd

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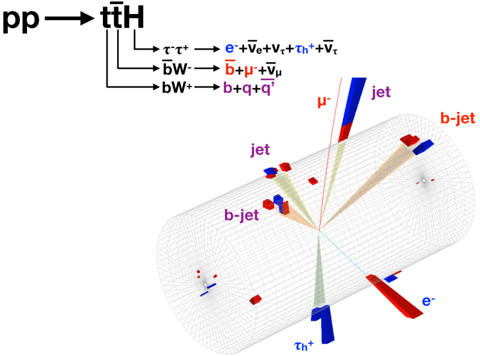
The search for $t\bar{t}H$



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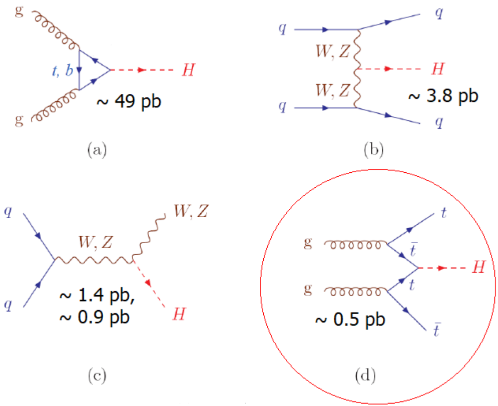
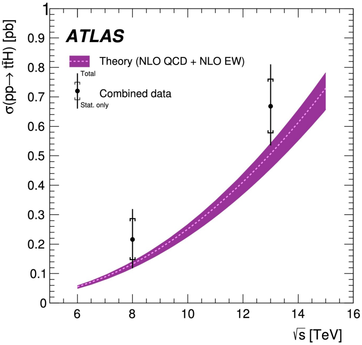
- Higgs boson discovery in 2012 by ATLAS & CMS
- Is it "the expected" Higgs boson? → potential door to BSM
- $t\bar{t}H$: special production process → low XS → finally observed at LHC



(b)

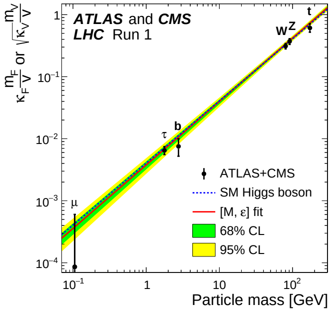
Assuming $m_H = 125$ GeV:

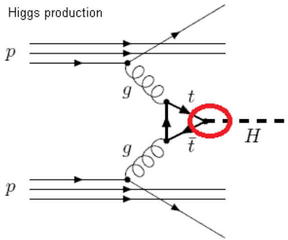


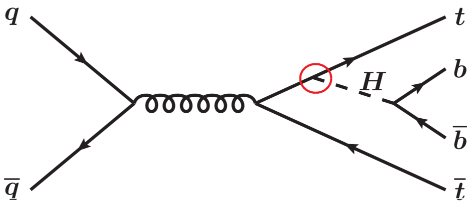
Introduction

The top Yukawa coupling

- Yukawa coupling $y_f \propto m_f$
- For top quark: $y_t \approx 1$
  $\Rightarrow$ potential window to BSM







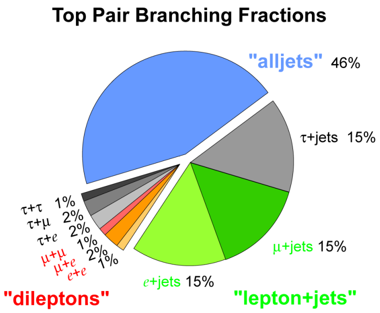
- gg fusion
  $\Rightarrow$ only indirect measurement

- $t\bar{t}H$ allows direct measurement

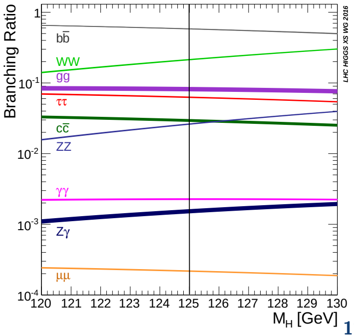
Introduction

Top and Higgs decays

- $\sigma_{\text{SM}}^{t\bar{t}H} = 507^{+35}_{-50}$ fb $\rightarrow$ only $\approx 1\%$ of Higgs produced at the LHC
    - Upside: additional $t\bar{t}$ pair provides more distinct topology, e.g. for $H \rightarrow b\bar{b}$
- Different top & Higgs decays $\rightarrow$ many different event topologies
    - Four main analyses in ATLAS, studying different Higgs decays:
    - $H \rightarrow b\bar{b}$, $H \rightarrow$ ML (multi-leptons), $H \rightarrow ZZ^* \rightarrow 4l$ (resonant), $H \rightarrow \gamma\gamma$



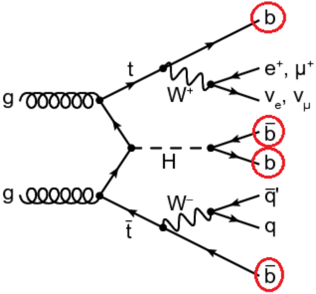
Higgs branching ratios:

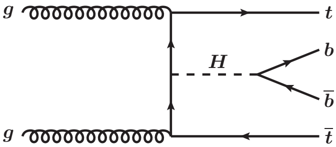


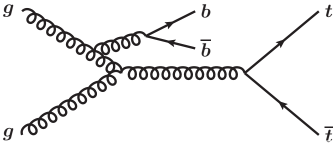
$t\bar{t}H(H \to b\bar{b})$

Phys. Rev. D 97, 072016 (2018)

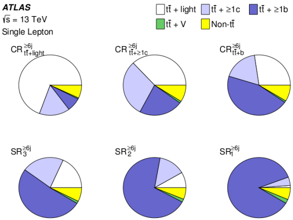
- Select single lepton and dilepton $t\bar{t}$ decay
- Complex final state $\to$ 4 or 6 jets including 4 b-jets at leading order!
- Largest background: $t\bar{t} +$ jets (light flavour, $c\bar{c}$, $b\bar{b}$ = “irreducible”)
  - Inclusive $t\bar{t}$ cross-section $\approx$ 3 orders of magnitude higher than signal
  - Analysis depends on discriminating $t\bar{t}H(H \to b\bar{b})$ from $t\bar{t} + b\bar{b}$

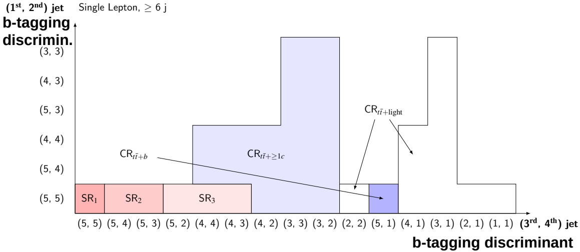






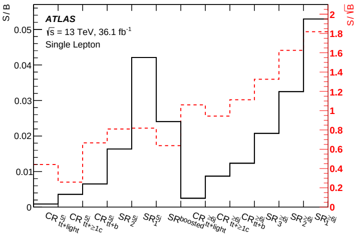
- Split channel using N_{jets} & $N_{b-\text{jets}}$ (different b-tagging working points) $\Rightarrow$ Regions enriched in $t\bar{t}$ + lf/$c\bar{c}$/$b\bar{b}$/Higgs
- High values of N_{jets} & $N_{b-\text{jets}}$: phase-space closer to signal region (SR) $\Rightarrow$ Other regions are control regions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

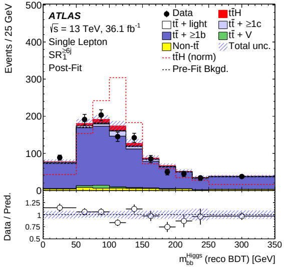


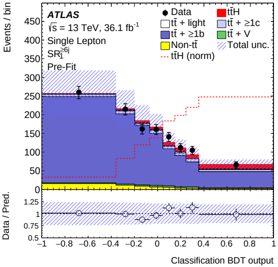


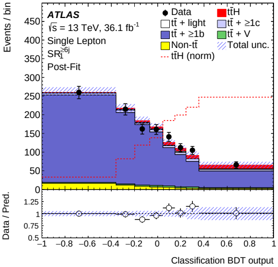
Single lepton regions with $N_{\text{jets}} \geq 6$
Highest signal purity: select 4 (very) tight b-tagged jets $\rightarrow$ "SR1"

- Final state reconstructed by BDT
  - Trained on $t\bar{t}H$ events only
  - Aiming to identify $b\bar{b}$ from Higgs
- Then fed into classification BDT
  - Discriminate $t\bar{t}H(H \rightarrow b\bar{b})$ vs. $t\bar{t} + b\bar{b}$
  - Reco BDT only 1 out of $O(20-30)$ variables in classification BDT





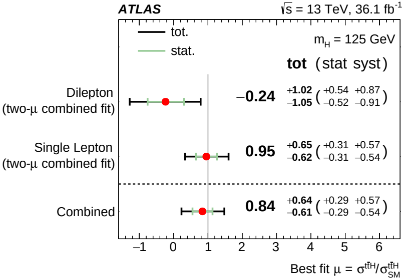


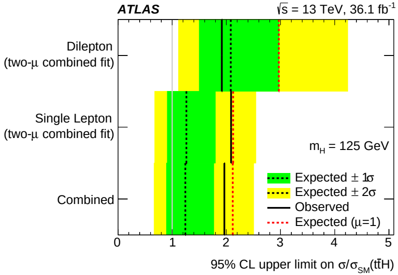


$t\bar{t}H(H \to b\bar{b})$

Results

- Fit signal strength $\mu = \sigma^{t\bar{t}H}/\sigma^{t\bar{t}H}_{\text{SM}} \Rightarrow 1.4\sigma$ observed (1.6σ expected)
- Systematically limited by MC modelling + background modelling stats
  - Estimating $t\bar{t} + b\bar{b}$ by comparing different MC generators
- Also: b-tagging, JES/JER, signal modelling
- No significant gain from more data → need to improve modelling and higher stats in MC





$t\bar{t}H(H \to \mathrm{ML})$

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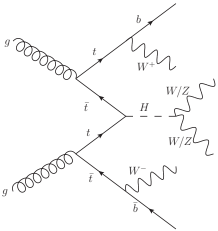
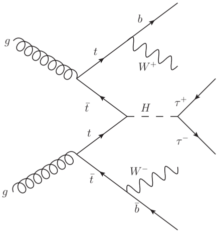
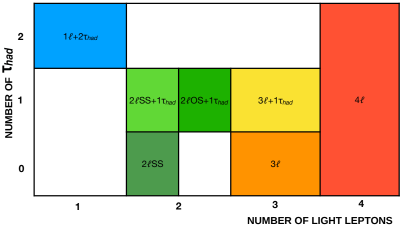
$t\bar{t}H(H \rightarrow \mathbf{ML})$

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_{leptons}, $N_{\tau_{\text{had}}}$, lepton charge
- Many different event topologies $\Rightarrow$ optimisation on many objects needed
- Systematic impact: leptons (prompt & non-prompt/fakes), MET, b-tagging, jets
- Veto $t\bar{t}H(H \rightarrow ZZ^* \rightarrow 4l) \rightarrow$ individual analysis

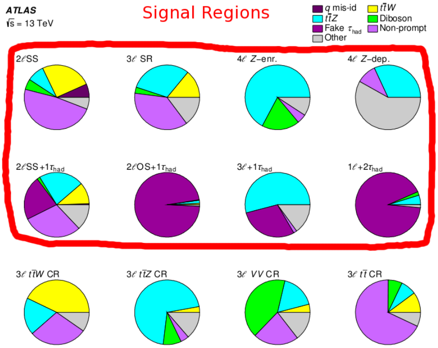


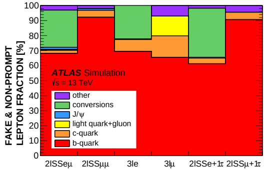


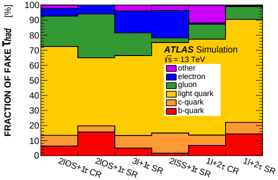


Two main background components:

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







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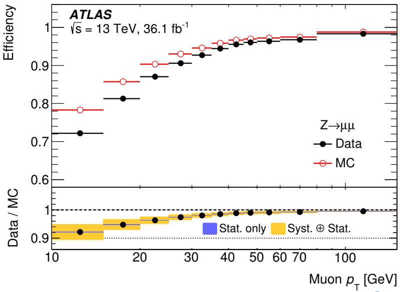
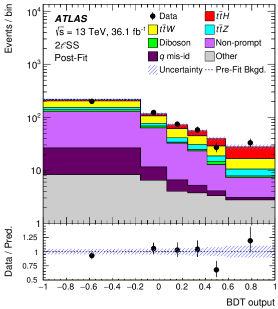
Two MVA stages:

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





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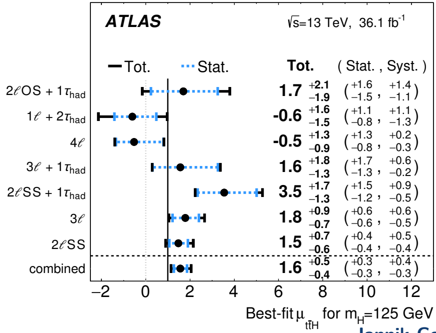
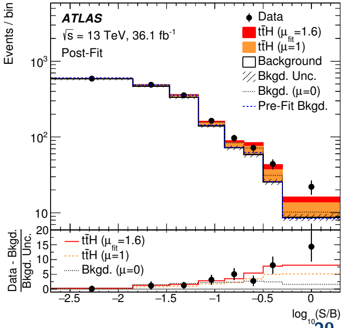
- 2 same-sign (light) leptons "2lSS" and 3 (light) leptons "3l"
  $\Rightarrow$ Most sensitive channels
- Dominant systematics: signal & background modelling, JES & JER, non-prompt light-lepton estimate, flavour-tagging, τ_{had}-ID
- Visible signal above background after combining channels
  $\Rightarrow$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





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

ATLAS-CONF-2019-004

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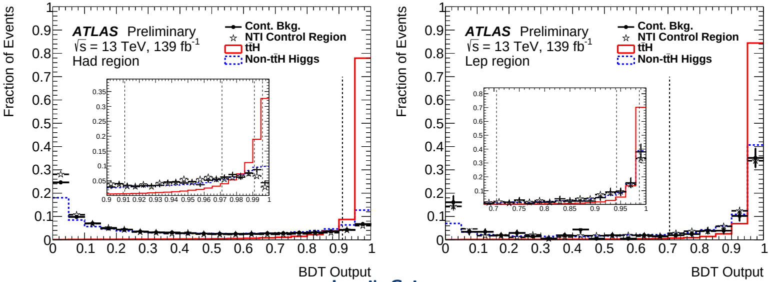
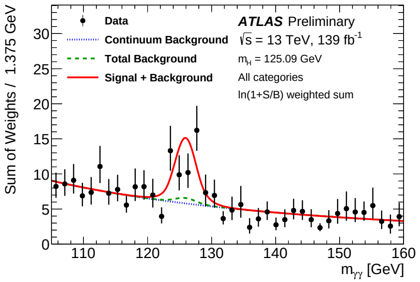
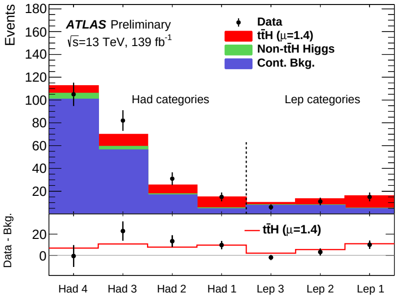
- Based on 139 fb^{-1} data, new analysis strategy wrt early Run II analysis
  - Similar to 79.8 fb^{-1} analysis, but updated photon ID & jet calibration
- Channel with low statistics: $\sigma \times \text{BR} = 0.507$ pb $\times$ 0.00227
- Select 2 tight γ & 1 b-jet & 1 lep ("Lep") or 2 jets and 0 lep ("Had")
- Backgrounds: non-resonant $\gamma\gamma$; tH & ggF (had); tH & VH (lep)
- One BDT trained per decay channel to discriminate signal vs. background
  - Train on $p_T^{\gamma}/m_{\gamma\gamma}$, using excellent resolution on $m_{\gamma\gamma}$ in [105 GeV-160 GeV]



- $\mu_{t\bar{t}H} = 1.38\ ^{+0.33}_{-0.31}(\text{stat.})^{+0.13}_{-0.11}(\text{exp.})^{+0.22}_{-0.14}(\text{theo.}) = 1.38^{+0.41}_{-0.36}$
  $\iff \sigma_{t\bar{t}H} \times \text{BR}_{\gamma\gamma} = 1.59^{+0.43}_{-0.39}$ fb
  - $4.9\sigma(4.2\sigma)$ observed (expected) → strong evidence, limited by statistics
- Dominant exp. uncertainties: photon energy scale & resolution; photon efficiency; Jet/$E_{\text{T}}^{\text{miss}}$ related uncertainties; background model
- Dominant theory uncert: signal model (UE & PS); HF model in non-$t\bar{t}H$





$t\bar{t}H(H \rightarrow \mathrm{ZZ}^* \rightarrow 4\mathrm{l})$ and combination with other channels

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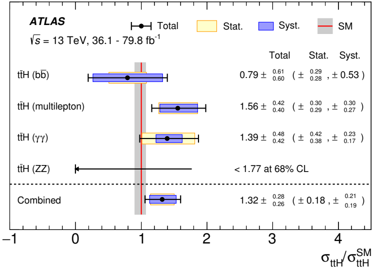
- Pure channel: S/B ≈ 125-300%, **BUT** $\sigma \times BR = 0.507$ pb $\times 0.0001251$
- Event selection similar to $t\bar{t}H(H \rightarrow \gamma\gamma) \rightarrow$ hadronic/leptonic regions
- Main backgrounds: $t\bar{t}W, t\bar{t}Z$ and non-$t\bar{t}H$ (ggF, tH)
- BDT with 2 bins in hadronic regions for 115 GeV $< m_{4l} <$ 130 GeV
  - Combined with lep region event yields as input to likelihood fit
- Expect 1 event, but 0 observed in data → more data needed → set limits: $\Rightarrow \mu_{t\bar{t}H} < 1.77 \Longleftrightarrow \sigma_{t\bar{t}H} < 900$ fb^{-1} @ 68% CL
- Dominant systematics: signal (PS) modelling, Higgs+HF modelling, JES

	Expected				Observed
Bin	$t\bar{t}H$ (signal)	Non-$t\bar{t}H$ Higgs	Non-Higgs	Total	Total
$H \rightarrow ZZ^* \rightarrow 4\ell$					
Had 1	0.169 ± 0.031	0.021 ± 0.007	0.008 ± 0.008	0.198 ± 0.033	0
Had 2	0.216 ± 0.032	0.20 ± 0.09	0.22 ± 0.12	0.63 ± 0.16	0
Lep	0.212 ± 0.031	0.0256 ± 0.0023	0.015 ± 0.013	0.253 ± 0.034	0



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-$t\bar{t}H$ Higgs boson production	1.5
Other background processes	2.2
Experimental uncertainties	9.3
Fake leptons	5.2
Jets, E_T^{miss}	4.9
Electrons, photons	3.2
Luminosity	3.0
τ-leptons	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4

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

- $t\bar{t}H$ production observed in ATLAS! → measurement compatible with SM

What you can take away

- Searches for $t\bar{t}Z, t\bar{t}W$ and $t\bar{t}H$ are very challenging
- Individual $t\bar{t}H$ analyses have their own challenges and limitations
  $\Rightarrow t\bar{t}H(H \rightarrow \text{ML})$ and $t\bar{t}H(H \rightarrow \gamma\gamma)$ have highest sensitivity
- ATLAS observed $t\bar{t}Z$ and $t\bar{t}H$ production $\rightarrow$ compatible with SM
  - Strong evidence for $t\bar{t}W$ production at 13 TeV (observed at 8 TeV)
- Next steps:
  - Current results use up to 79.8 fb^{-1} data $\rightarrow$ use full Run II data (139 fb^{-1})
  - Develop improved analyses techniques
  - Extract top Yukawa coupling and t-Z NC EW coupling (sensitive to I_3^W)

Fit configuration	$\mu_{t\bar{t}Z}$	$\mu_{t\bar{t}W}$
Combined	1.08 ± 0.14	1.44 ± 0.32
2ℓ-OS	0.73 ± 0.28	–
$3\ell\ t\bar{t}Z$	1.08 ± 0.18	–
2ℓ-SS and $3\ell\ t\bar{t}W$	–	1.41 ± 0.33
4ℓ	1.21 ± 0.29	–

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

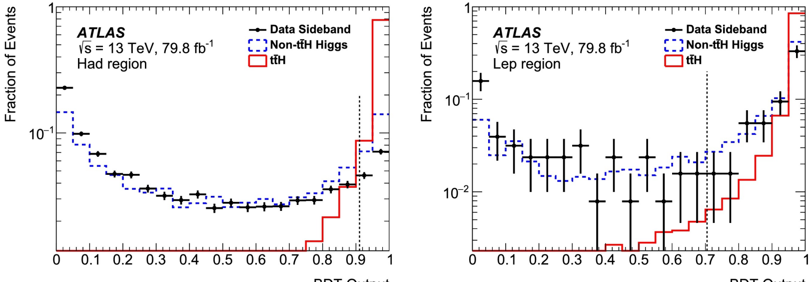
Thank you!

Backup

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

Overview & strategy of 79.8 fb^{-1} analysis

- Based on 79.8 fb^{-1} data, new analysis strategy wrt old analysis
- Channel with <u>low</u> statistics: $\sigma \times \text{BR} = 0.507\ \text{pb} \times 0.00227$
- Select $\gamma\gamma$ & various N_{jets}, $N_{b-\text{tags}}$, N_{lep} $\to$ <u>hadronic</u> & semi-lep $t\bar{t}$ regions
- Backgrounds: non-resonant $\gamma\gamma$; tH & ggF (had); tH & VH (lep)
- One BDT trained per decay channel to discriminate signal vs. background
    - Train on $p_T^{\gamma}/m_{\gamma\gamma}$, using excellent resolution on $m_{\gamma\gamma}$ in [105 GeV-160 GeV]

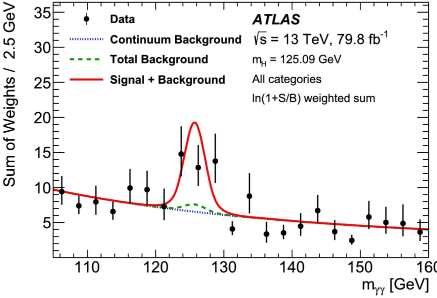


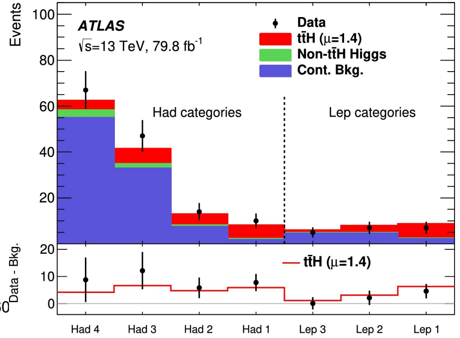
(a) (b)

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

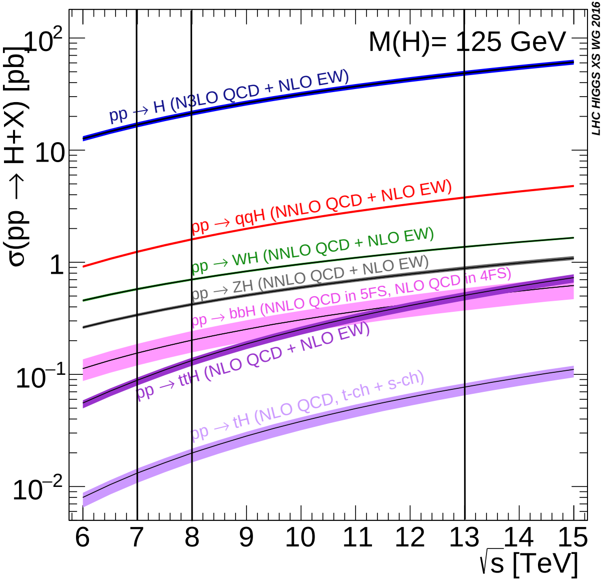
Results of 79.8 fb^{-1} analysis

- $\mu_{t\bar{t}H} = 1.39\,^{+0.42}_{-0.38}(\text{stat.})^{+0.23}_{-0.17}(\text{syst.})$
  - $4.1\sigma(3.7\sigma)$ observed (expected) $\to$ strong evidence, limited by statistics
- Dominant theory uncertainty: signal (PS) modelling; Higgs+HF modelling
- Dominant exp. unc: JER/JES, photon isolation, energy scale & resolution





1. MVA against non-prompt leptons
    - Used in SS dilepton and $t\bar{t}W$ trilepton channels
    - Distinguish prompt leptons from those from heavy-hadron decays in jets
    - Use information from charged-particle tracks in a cone around the lepton candidate
        - Jets are reconstructed from these tracks
        - MVA trained on e.g. angular distance between lep & track jet, number of tracks in track jet, ratio of lepton p_T to track jet p_T
    - Rejection factor for leptons from b-hadron decays ≈ 20
    - Prompt lepton efficiency: 85% (80%) for muons (electrons) with $p_T \approx 20$ GeV $\Rightarrow$ reaches plateau of $\approx$ 98% (96%) at high p_T
2. MVA against charge-flipped electrons
    - Uses various track and cluster properties of electron candidates
    - 95% efficiency for electrons with correct charge reconstruction
    - Rejection factor of ≈ 17 for electrons with misidentified charge that pass the tight likelihood identification requirement



M(H)= 125 GeV
LHC HIGGS XS WG 2016
pp → H (N3LO QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD + NLO EW)
pp → bbH (NNLO QCD in 5FS, NLO QCD in 4FS)
pp → ttH (NLO QCD + NLO EW)
pp → tH (NLO QCD, t-ch + s-ch)
σ(pp → H+X) [pb]
10^2
10
1
10^{-1}
10^{-2}
6
7
8
9
10
11
12
13
14
15
√s [TeV]