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

Jannik Geisen
on behalf of the ATLAS collaboration

II. Physikalisches Institut, Georg-August-Universität Göttingen

16th of July at QCD@LHC 2019
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 ($e, \mu$)
   - 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
$t\bar{t}Z$ and $t\bar{t}W$

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

- Rare processes with small cross-section $\rightarrow$ 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 $\rightarrow$ XS can be used to set constraints on couplings
- Background in searches such as:
  - Final states containing multiple leptons and $b$-quarks
  - $t \bar{t} H$

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

<table>
<thead>
<tr>
<th>Process</th>
<th>( t\bar{t} ) decay</th>
<th>Boson decay</th>
<th>Channel</th>
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<tbody>
<tr>
<td>( t\bar{t}W )</td>
<td>((\ell^\pm \nu b)(q\bar{q}b))</td>
<td>( \ell^\pm \nu )</td>
<td>SS dilepton</td>
</tr>
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<td>((\ell^\pm \nu b)(\ell^\mp \nu b))</td>
<td>( \ell^\pm \nu )</td>
<td>Trilepton</td>
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<tr>
<td>( t\bar{t}Z )</td>
<td>((q\bar{q}b)(q\bar{q}b))</td>
<td>( \ell^+ \ell^- )</td>
<td>OS dilepton</td>
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<td>( \ell^+ \ell^- )</td>
<td>Tetralepton</td>
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• 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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<th>Backgrounds</th>
<th>Estimation strategy</th>
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<tr>
<td><strong>OS dilepton</strong></td>
<td>$Z+\text{jets}$</td>
<td>$Z+0$ heavy flavour (HF) from MC, $Z+1(+2)$ HF from fit to data in CR; dedicated CR (select $e\mu$)</td>
</tr>
<tr>
<td>Use BDT to discriminate signal from background</td>
<td>$t\bar{t}$</td>
<td></td>
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<tr>
<td><strong>Trilepton</strong></td>
<td>$WZ, ZZ$</td>
<td>CR to estimate norm. in data;</td>
</tr>
<tr>
<td>four signal regions (SR)</td>
<td>$tZ, tWZ$</td>
<td>estimated from MC;</td>
</tr>
<tr>
<td>incl. off-shell $Z^<em>/\gamma^</em>$</td>
<td>$Z+\text{jets}$ with fake lep</td>
<td>estimated from MC</td>
</tr>
<tr>
<td><strong>Tetralepton</strong></td>
<td>Fake leptons</td>
<td>estimated in MC, corrected by SF determined from two CR;</td>
</tr>
<tr>
<td>select 2 OS lep pairs, at least 1 same flavour (SF)</td>
<td>$ZZ$</td>
<td>CR to estimate norm. in data</td>
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#### Graphs

- **ATLAS** $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
  - **3L-WZ-CR (pre-fit)**
  - **Data**, $t\bar{t}$, $WZ$, $ZZ$, $tZ$, fake leptons, other uncertainties

- **ATLAS** $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
  - **3L-WZ-CR**
  - **Data**, $tZ$, $ZZ$, $tWZ$, fake leptons, other uncertainties

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<td>Split regions based on charge</td>
<td>Charge-flip</td>
<td>dedicated CR and validation region</td>
</tr>
<tr>
<td>($W$ preferably positive, background charge symmetric)</td>
<td>(significant in ee regions)</td>
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<td>Veto on $Z$ mass</td>
<td>other SM processes</td>
<td>estimated from MC</td>
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<tr>
<td>for OSSF lepton pair</td>
<td>with 3 prompt leptons</td>
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<tr>
<td>regions split by total charge</td>
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**ATLAS**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- 2e-SS-1b-VR (pre-fit)

- **Data**
- $t\bar{t}W$
- Other
- $\gamma + X$
- Charge-flips
- Fake Leptons
- Uncertainty

**CR DEFINED BY REMOVING “HT > 240 GeV” AND REQUIRING 1-3 JETS INSTEAD OF \( \geq 4 \) JETS WRT 2e SR**

- Events / 20 GeV

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<th>$m_{ll}$ [GeV]</th>
<th>0</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
<th>120</th>
<th>140</th>
<th>160</th>
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**ATLAS**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- 3Lp-noZ2j (pre-fit)

- **Data**
- $t\bar{t}W$
- Other
- $\gamma + X$
- Fake Leptons
- Uncertainty

**ALL 4 SIGNAL REGIONS TARGETING $t\bar{t}W$**

- Events / 20 GeV

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<th>$E_T^{miss}$ [GeV]</th>
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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

⇒ Individual fit results compatible with combined result within $1\sigma$
\[ \mu = \sigma_{\text{measured}} / \sigma_{\text{SM}} \]

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<th>Fit configuration</th>
<th>( \mu_{t\bar{t}Z} )</th>
<th>( \mu_{t\bar{t}W} )</th>
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<tbody>
<tr>
<td>Combined</td>
<td>1.08 ± 0.14</td>
<td>1.44 ± 0.32</td>
</tr>
<tr>
<td>2\ell-OS ( t\bar{t}Z )</td>
<td>0.73 ± 0.28</td>
<td>–</td>
</tr>
<tr>
<td>3\ell ( t\bar{t}Z )</td>
<td>1.08 ± 0.18</td>
<td>–</td>
</tr>
<tr>
<td>2\ell-SS and 3\ell ( t\bar{t}W )</td>
<td>–</td>
<td>1.41 ± 0.33</td>
</tr>
<tr>
<td>4\ell</td>
<td>1.21 ± 0.29</td>
<td>–</td>
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- Use SM prediction to translate \( \mu \) 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 5\( \sigma \) significance; \( t\bar{t}W \) 4.3\( \sigma \) obs. (3.4\( \sigma \) exp.) \( \rightarrow \) evidence
Sources of uncertainty

<table>
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<tr>
<th>Uncertainty</th>
<th>$\sigma_{ttZ}$</th>
<th>$\sigma_{ttW}$</th>
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<td>Luminosity</td>
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- **Most significant systematics:**
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- **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 $ttZ$: bkgd modelling; signal modelling
  - Most dominant in $ttW$: signal modelling; limited statistics in data CR & MC samples; fake lepton & charge-flip bkgd

- **Systematics implemented as NP constrained by Gaussian PDFs**
- **Most NP found not sign. constrained/pulled by fit**
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- Most significant systematics:
  - Fake leptons, esp. in $\tilde{t}\tilde{W}$ from using the matrix method
  - Charge-flip probability through $ee$ events with $m_\| \approx m_Z$
- 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 $\tilde{t}\tilde{Z}$: bkgd modelling; signal modelling
  - Most dominant in $\tilde{t}\tilde{W}$: signal modelling; limited statistics in data CR & MC samples; fake lepton & charge-flip bkgd
Sources of uncertainty

- Systematics implemented as NP constrained by Gaussian PDFs
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<td>$\ttW$ modeling</td>
<td>0.3%</td>
<td><strong>8.5%</strong></td>
</tr>
<tr>
<td>Total systematic</td>
<td><strong>10%</strong></td>
<td>16%</td>
</tr>
<tr>
<td>Statistical</td>
<td>8.4%</td>
<td><strong>15%</strong></td>
</tr>
<tr>
<td>Total</td>
<td><strong>13%</strong></td>
<td>22%</td>
</tr>
</tbody>
</table>

- Systematics implemented as NP constrained by Gaussian PDFs
- Most NP found not sign. constrained/pulled by fit
- Most significant systematics:
  - Fake leptons, esp. in $\ttW$ from using the matrix method
  - Charge-flip probability through $ee$ events with $m_\lll \approx m_Z$
- Normalisation correction factors for $WZ$, $ZZ$, $Z+1$HF, $Z+2$HF compatible with 1
- Syst. & stat. uncertainties for both processes roughly in same order
  - Most dominant in $\ttZ$: bkgd modelling; signal modelling
  - Most dominant in $\ttW$: signal modelling; limited statistics in data CR & MC samples; fake lepton & charge-flip bkgd
The search for $t\bar{t}H$
Introduction
Higgs production at the LHC

- 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

Assuming $m_H = 125$ GeV:

(a) $\sim 49$ pb
(b) $\sim 3.8$ pb
(c) $\sim 1.4$ pb, $\sim 0.9$ pb
(d) $\sim 0.5$ pb

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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

**Diagram: ATLAS and CMS LHC Run 1**

Particle mass [GeV]

$1 \to 10^{-1}, 10, 10^2$

$\kappa_{F,V}$ or $|\kappa_{F,V}|$

$10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}$

$W^\pm, Z, \tau, b, \mu$

SM Higgs boson

$68\% \text{ CL}, 95\% \text{ CL}$

Run 1

LHC

CMS and ATLAS
Introduction

Top and Higgs decays

- $\sigma_{t\bar{t}H}^{SM} = 507^{+35}_{-50}$ fb → only ≈ 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 → 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:

![Higgs branching fractions graph](image-url)
$t\bar{t}H(H \rightarrow b\bar{b})$

Details and challenges

- Select single lepton and dilepton $t\bar{t}$ decay
- Complex final state $\rightarrow$ 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 $t\bar{t}H(H \rightarrow b\bar{b})$ from $t\bar{t} + b\bar{b}$
**Analysis strategy**

- Split channel using $N_{\text{jets}}$ & $N_{\text{b-jets}}$ (different $b$-tagging working points)
  ⇒ Regions enriched in $t\bar{t} + \ell f/c\bar{c}/bb$/$Higgs$

- High values of $N_{\text{jets}}$ & $N_{\text{b-jets}}$: phase-space closer to signal region (SR)
  ⇒ 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 → "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
$t\bar{t}H(H \rightarrow b\bar{b})$

**Results**

- Fit signal strength $\mu = \sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}^{\text{SM}} \Rightarrow 1.4\sigma$ observed (1.6\sigma 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 $\rightarrow$ need to improve modelling and higher stats in MC

---

**Graphical Representation**

- **ATLAS**
- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- $m_H = 125$ GeV
- Best fit $\mu = \sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}^{\text{SM}}$
- **Dilepton** (two-$\mu$ combined fit)
  - $-0.24^{+1.02}_{-1.05}$
- **Single Lepton** (two-$\mu$ combined fit)
  - $0.95^{+0.65}_{-0.62}$
- **Combined**
  - $0.84^{+0.64}_{-0.61}$

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\[ t\bar{t}H(H \rightarrow ML) \]

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

- Prompt leptons → estimate via MC: $t\bar{t}W$, $t\bar{t}Z$, Diboson
- Fake $\tau_{\text{had}}$; fake & non-prompt (light) leptons; charge mis-ID (electrons) ⇒ data-driven estimate
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 $t\bar{t}H(H \rightarrow ML)$ vs. backgrounds
  - Combine multiple BDTs with multi-dimensional binning
t\bar{t}H(H \rightarrow ML)

Results

- 2 same-sign (light) leptons “2\ell SS” and 3 (light) leptons “3\ell”
  ⇒ Most sensitive channels

- Dominant systematics: signal & background modelling, JES & JER, non-prompt light-lepton estimate, flavour-tagging, \( \tau_{\text{had}} \)-ID

- Visible signal above background after combining channels
  ⇒ Significance: 4.1\( \sigma \) observed, 2.8\( \sigma \) expected

\( \sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \)

\begin{align*}
\text{ATLAS} & \quad \text{Events / bin} \\
2\ell\text{OS} + 1\tau_{\text{had}} & \quad \text{Stat.} \\
1\ell + 2\tau_{\text{had}} & \quad \text{Tot.} (\text{Stat.}, \text{Syst.}) \\
4\ell & \quad 1.7 \pm 2.1 (\pm 1.6, \pm 1.4) \\
3\ell + 1\tau_{\text{had}} & \quad -0.6 \pm 1.6 (\pm 1.1, \pm 1.1) \\
2\ell\text{SS} + 1\tau_{\text{had}} & \quad 1.6 \pm 1.5 (\pm 0.8, \pm 1.3) \\
3\ell & \quad -0.5 \pm 1.3 (\pm 0.8, \pm 0.3) \\
2\ell\text{SS} & \quad 1.5 \pm 0.9 (\pm 0.6, \pm 0.9) \\
\text{combined} & \quad 1.6 \pm 0.4 (\pm 0.3, \pm 0.3)
\end{align*}

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$t\bar{t}H(H \rightarrow \gamma\gamma)$
Overview and strategy

- 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: $\sigma \times \text{BR} = 0.507 \text{ pb} \times 0.00227$
- Select 2 tight $\gamma$ & 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]
$t\bar{t}H(\gamma\gamma)$

**Results**

- $\mu_{t\bar{t}H} = 1.38^{+0.33}_{-0.31}^{\text{stat.}}^{+0.13}_{-0.11}^{\text{exp.}}^{+0.22}_{-0.14}^{\text{theo.}} = 1.38^{+0.41}_{-0.36}$

  $\iff \sigma_{t\bar{t}H} \times \text{BR}_{\gamma\gamma} = 1.59^{+0.43}_{-0.39} \text{ fb}$

- $4.9\sigma(4.2\sigma)$ observed (expected) $\implies$ strong evidence, limited by statistics

- Dominant exp. uncertainties: photon energy scale & resolution; photon efficiency; Jet/$E_T^{\text{miss}}$ related uncertainties; background model

- Dominant theory uncert: signal model (UE & PS); HF model in non-$t\bar{t}H$
$t\bar{t}H(H \rightarrow ZZ^* \rightarrow 4l)$
and combination with other channels

**Overview and results**

- Pure channel: \( S/B \approx 125-300\% \), **BUT** \( \sigma \times \text{BR} = 0.507 \text{ pb} \times 0.0001251 \)
- Event selection similar to \( t\bar{t}H(H \to \gamma\gamma) \to \text{hadronic/leptonic regions} \)
- 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 \( 115 \text{ GeV} < m_{4\ell} < 130 \text{ GeV} \)
  - Combined with lep region event yields as input to likelihood fit
- Expect 1 event, but 0 observed in data → **more data needed** → set limits: \( \mu_{t\bar{t}H} < 1.77 \Leftarrow \sigma_{t\bar{t}H} < 900 \text{ fb}^{-1} \) @ 68% CL
- Dominant systematics: signal (PS) modelling, Higgs+HF modelling, JES

<table>
<thead>
<tr>
<th>Bin</th>
<th>( t\bar{t}H ) (signal)</th>
<th>Non-( t\bar{t}H ) Higgs</th>
<th>Non-Higgs</th>
<th>Total</th>
<th>Observed Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Had 1</td>
<td>0.169 ± 0.031</td>
<td>0.021 ± 0.007</td>
<td>0.008 ± 0.008</td>
<td>0.198 ± 0.033</td>
<td>0</td>
</tr>
<tr>
<td>Had 2</td>
<td>0.216 ± 0.032</td>
<td>0.20 ± 0.09</td>
<td>0.22 ± 0.12</td>
<td>0.63 ± 0.16</td>
<td>0</td>
</tr>
<tr>
<td>Lep</td>
<td>0.212 ± 0.031</td>
<td>0.0256 ± 0.0023</td>
<td>0.015 ± 0.013</td>
<td>0.253 ± 0.034</td>
<td>0</td>
</tr>
</tbody>
</table>
**t\bar{t}H** combination

Final combined results

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

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Jannik Geisen
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 $I_3^W$)

<table>
<thead>
<tr>
<th>Fit configuration</th>
<th>$\mu_{t\bar{t}Z}$</th>
<th>$\mu_{t\bar{t}W}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined</td>
<td>1.08 ± 0.14</td>
<td>1.44 ± 0.32</td>
</tr>
<tr>
<td>$2\ell$-OS</td>
<td>0.73 ± 0.28</td>
<td>–</td>
</tr>
<tr>
<td>$3\ell$ $t\bar{t}Z$</td>
<td>1.08 ± 0.18</td>
<td>–</td>
</tr>
<tr>
<td>$2\ell$-SS and $3\ell$ $t\bar{t}W$</td>
<td>–</td>
<td>1.41 ± 0.33</td>
</tr>
<tr>
<td>$4\ell$</td>
<td>1.21 ± 0.29</td>
<td>–</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Integrated luminosity [fb$^{-1}$]</th>
<th>$t\bar{t}H$ cross section [fb]</th>
<th>Obs. sign.</th>
<th>Exp. sign.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>79.8</td>
<td>710 $^{+210}<em>{-190}$ (stat.) $^{+120}</em>{-90}$ (syst.)</td>
<td>4.1$\sigma$</td>
<td>3.7$\sigma$</td>
</tr>
<tr>
<td>$H \rightarrow$ multilepton</td>
<td>36.1</td>
<td>790 ±150 (stat.) $^{+150}_{-140}$ (syst.)</td>
<td>4.1$\sigma$</td>
<td>2.8$\sigma$</td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>36.1</td>
<td>400 $^{+150}_{-140}$ (stat.) ± 270 (syst.)</td>
<td>1.4$\sigma$</td>
<td>1.6$\sigma$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$</td>
<td>79.8</td>
<td>&lt;900 (68% CL)</td>
<td>0$\sigma$</td>
<td>1.2$\sigma$</td>
</tr>
</tbody>
</table>

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$\sigma$
Thank you!
Backup
Overview & strategy of 79.8 fb$^{-1}$ analysis

- Based on 79.8 fb$^{-1}$ data, new analysis strategy wrt old analysis
- Channel with low statistics: $\sigma \times \text{BR} = 0.507 \text{ pb} \times 0.00227$
- Select $\gamma\gamma$ & various $N_{\text{jets}}, N_{b\text{-tags)}, N_{\text{lep}} \rightarrow \text{hadronic}$ & 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]

![Graphs showing the analysis strategy](a) Had region (b) Lep region
$t\bar{t}H(H \rightarrow \gamma\gamma)$

Results of 79.8 fb$^{-1}$ analysis

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

![Graph showing $m_{\gamma\gamma}$ distribution and event counts for different categories, with comparison to data and background expectations.](image-url)
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 $\approx 20$
   - 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 $\approx 17$ for electrons with misidentified charge that pass the tight likelihood identification requirement
t\bar{t}H - Introduction
Various Higgs cross-sections at LHC

\[ \sigma(pp \rightarrow H + X) \ [pb] \]

\[ \sigma(pp \rightarrow ttH) \ [pb] \]

\[ M(H) = 125 \text{ GeV} \]

\[ \sqrt{s} \ [TeV] \]

- \[ pp \rightarrow H \ (N^3LO \ QCD \ + \ NLO \ EW) \]
- \[ pp \rightarrow qqH \ (NNLO \ QCD \ + \ NLO \ EW) \]
- \[ pp \rightarrow WH \ (NNLO \ QCD \ + \ NLO \ EW) \]
- \[ pp \rightarrow ZH \ (NNLO \ QCD \ + \ NLO \ EW) \]
- \[ pp \rightarrow bbH \ (NNLO \ QCD \ in \ 5FS, \ NLO \ QCD \ in \ 4FS) \]
- \[ pp \rightarrow tH \ (NLO \ QCD, \ t-ch + s-ch) \]
- \[ pp \rightarrow ttH \ (NLO \ QCD \ + \ NLO \ EW) \]

LHC Higgs XS WG 2016

Jannik Geisen