Measurement of Higgs boson production in association with two top quarks (ttH) in the H→γγ channel using 139 fb⁻¹ of data collected with the ATLAS detector

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Higgs-top Yukawa coupling

- A probe of fundamental interest: the Yukawa coupling between the Higgs boson and the top quark, the heaviest particle in SM
- Higgs-top Yukawa coupling can be indirectly probed via the gluon-fusion production cross section and $H\rightarrow\gamma\gamma$ decay branch ratio (loop-level processes)
- BSM particles could be present in the loop
**t\bar{t}H production mode**

- A **more direct test** of this coupling can be performed through the production of the Higgs boson in association with a top quark pair (t\bar{t}H).
- A very rare Higgs production mode (~1%; 507 fb at 13 TeV); mainly a tree-level process.
- Could get handles on BSM physics by comparison between loop-induced processes and direct t\bar{t}H production.
Study $t\bar{t}H$ production

- Need to consider different Higgs boson decay channels for such a rare production mode!
  - $t\bar{t}H, \ H \rightarrow ZZ^* \rightarrow 4$-lepton
  - $t\bar{t}H, \ H \rightarrow \gamma\gamma$
  - $t\bar{t}H$, multi-lepton ($H \rightarrow WW^*, \tau\tau, ZZ^*$, excluding $ZZ^* \rightarrow 4$-lepton, see Rohin’s talk later)
  - $t\bar{t}H, \ H \rightarrow b\bar{b}$

**Top Pair Branch Fractions**

- "alljets" 46%
- $\tau+\text{jets}$ 15%
- $\mu+\text{jets}$ 15%
- "dileptons" 15%
- "lepton+jets" 15%

**Higgs Branch Fractions**

- $WW$ 21%
- $gg$ 9%
- $\tau\tau$ 6%
- $cc$ 3%
- $ZZ$ 3%
- Other 1%
- $bb$ 57%
This talk:
$t\bar{t}H (H\rightarrow\gamma\gamma) \ (139 \ fb^{-1})$
**t\(\bar{t}H\) (H\(\rightarrow\gamma\gamma\)) analysis strategy**

Select events with **two photons** and at least one b-jet

➔ Separate to **hadronic channel** \((n_{\text{lep}} = 0)\) and **leptonic channel** \((n_{\text{lep}} \geq 1)\)

  • Background: continuum bkg. \((\gamma\gamma, t\bar{t}\gamma\gamma, \text{etc.})\) and resonant bkg. from other Higgs production modes \((ggH, tH, \text{etc.})\)

➔ In each channel, train a Boost Decision Tree (BDT) with XGBoost package to separate t\(\bar{t}H\) signal from backgrounds

  • define **event categories based on BDT output**

➔ Fit **diphoton mass** over all categories

  • robust continuum background estimation from data sidebands; narrow signal peaks around Higgs boson mass

➔ Measure t\(\bar{t}H\) production signal strength, etc.
Hadronic channel

- Target: all-hadronic top-quark pair decays, or semi-leptonic top-quark pair decays with leptons not identified
- BDT trained with t\bar{t}H simulation and data control region having photons failing identification, using:
  - $p_T$, $\eta$, $\phi$, and b-tag status of first 6 jets (sorted by $p_T$)
  - MET and $\phi$(MET)
  - $p_T/\gamma\gamma$, $\eta$, and $\phi$ of 2 photons

- Events with low BDT score are vetoed
- Define 4 categories in hadronic channel based on BDT output, to exploit its good separation power
Leptonic channel

- Target: semi-leptonic top-quark pair decays
- BDT trained with $t\bar{t}H$ simulation and data control region having photons failing identification, using:
  - $p_T$, $\eta$, $\phi$ of first 4 jets, first 2 leptons (sorted by $p_T$)
  - MET and $\phi$(MET)
  - $p_T/m_{\gamma\gamma}$, $\eta$, and $\phi$ of 2 photons

- Events with low BDT score are vetoed
- Define 3 categories in leptonic channel based on BDT output, to exploit its good separation power
Signal and background modeling

- For each event category, need to model diphoton mass distributions of signal and backgrounds

- **Model of \( \ttH \) signal and non-\( \ttH \) Higgs background**
  - Expected yields from \( \ttH \) and non-\( \ttH \) production modes estimated from simulation
  - Mass shapes: parametrized from simulation with double-sided crystal ball functions

- **Model of continuum background**:
  - Analytical functions fitted on (unbinned) data
  - Using dedicated background-only samples
    - checked the BDTs do not induce a bump
    - studied functional forms and associated uncertainties
Diphoton mass: individual category

Had BDT1

- Had BDT1 (category with highest S/B in hadronic channel):
  - expect 6.9 $t\bar{t}H$ events, 5.3 background events, observe 15 events, in the mass window containing 90% of the signals
Lep BDT1 (category with highest S/B in leptonic channel):
- expect 7.9 $t\bar{t}H$ events, 5.0 background events, observe 15 events, in the mass window containing 90% of the signals
• Diphoton mass spectrum peaks at the Higgs mass around 125 GeV
• \( \sim 53 \) \( \bar{t}tH \) (\( H \rightarrow \gamma\gamma \)) events fitted over 7 categories, in the mass window containing 90% of the signals
Event yields: all categories

- Number of events in each category, in the mass window containing 90% of the signal events

Expected S/B: 0.05, 0.13, 0.32, 1.6, 0.18, 0.49, 1.6
t\(\bar{t}tH (H \rightarrow \gamma\gamma)\) results: significance

<table>
<thead>
<tr>
<th>t(\bar{t}H, H \rightarrow \gamma\gamma)</th>
<th>expected significance</th>
<th>observed significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>36 fb(^{-1}) results PRD 98 (2018) 052005</td>
<td>1.7(\sigma)</td>
<td>0.9(\sigma)</td>
</tr>
<tr>
<td>139 fb(^{-1}) result ATLAS-CONF-2019-004</td>
<td>4.2(\sigma)</td>
<td>4.9(\sigma)</td>
</tr>
</tbody>
</table>

- The new t\(\bar{t}H (H \rightarrow \gamma\gamma)\) analysis has **better sensitivity** than the 36 fb\(^{-1}\) publication (PRD 98 (2018) 052005), for the same luminosity.
- The largest sensitivity improvement is achieved by using **kinematic information of jets, leptons, photons and MET** as inputs to BDT.
Example variables in BDT training

- Signal and background differ in kinematic variables of jets, leptons, photons and MET
- BDT can also utilize correlation between training variables
Example variables for BDT validation

- The distributions of data in best BDT categories follow the distributions of $t\bar{t}H$ simulation.
- These variables are for validation and not directly used in analysis.
t\bar{t}H signal strength measurement

• The t\bar{t}H signal strength is measured to be
  \[ 1.38^{+0.41}_{-0.36} = 1.38^{+0.33}_{-0.31} \text{(stat.)}^{+0.13}_{-0.11} \text{(exp.)}^{+0.22}_{-0.14} \text{(theo.)} \]

• The t\bar{t}H total cross section times the H\rightarrow\gamma\gamma branch ratio is measured to be
  \[ 1.59^{+0.43}_{-0.39} \text{ fb} = 1.59^{+0.38}_{-0.36} \text{(stat.)}^{+0.15}_{-0.12} \text{(exp.)}^{+0.15}_{-0.11} \text{(theo.) fb} \]
  \[ \sim25\% \text{ precision} \]
  \[ \text{in agreement with the NLO SM prediction of} \ 1.15^{+0.09}_{-0.12} \text{ fb} \]
Breakdown of systematic uncertainties

- This channel is still **statistically limited**
  - Parton showering and photon energy resolution systematics are the highest ranked ones

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta \sigma_{\text{low}}/\sigma$ [%]</th>
<th>$\Delta \sigma_{\text{high}}/\sigma$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory uncertainties</td>
<td></td>
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<tr>
<td>Underlying Event and Parton Shower (UEPS)</td>
<td>5.0</td>
<td>7.2</td>
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<tr>
<td>Modeling of Heavy Flavor Jets in non-$t\bar{t}H$ Processes</td>
<td>4.0</td>
<td>3.4</td>
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<td>Higher-Order QCD Terms (QCD)</td>
<td>3.3</td>
<td>4.7</td>
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<td>Parton Distribution Function and $\alpha_S$ Scale (PDF+$\alpha_S$)</td>
<td>0.3</td>
<td>0.5</td>
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<tr>
<td>Non-$t\bar{t}H$ Cross Section and Branching Ratio to $\gamma\gamma$ (BR)</td>
<td>0.4</td>
<td>0.3</td>
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<tr>
<td>Experimental uncertainties</td>
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<td>Photon Energy Resolution (PER)</td>
<td>5.5</td>
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<td>Photon Energy Scale (PES)</td>
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<td>Jet/$E_T^{\text{miss}}$</td>
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<td>Photon Efficiency</td>
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<td>Background Modeling</td>
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<td>Flavor Tagging</td>
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<td>Leptons</td>
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<td>Pileup</td>
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<td>Luminosity and Trigger</td>
<td>1.6</td>
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<tr>
<td>Higgs Boson Mass</td>
<td>1.6</td>
<td>1.5</td>
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Summary

- ATLAS measured the $t\bar{t}H$ (H→γγ) process using the **full Run-2 data set**
- We use kinematic information of jets, leptons, photons and MET with advanced **machine learning** algorithm XGBoost BDT, to improve the sensitivity of this analysis
- The $t\bar{t}H$ production is observed in the H→γγ decay mode with a **4.9σ observed significance**
- The signal strength and the $t\bar{t}H$ cross section times H→γγ branch ratio measurements are in agreement with the SM predictions
Display: $\tilde{t}\tilde{t}H \,(H\rightarrow\gamma\gamma)$ Had1 candidate event

- $\tilde{t}\tilde{t}H \,(H\rightarrow\gamma\gamma)$ Had1 candidate, with $m_{\gamma\gamma} = 125.4$ GeV and six jets; $S/B \,(\text{Had1}) \sim 2$