Wild Card ATLAS

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On behalf of the ATLAS Collaboration

54th Rencontres de Moriond
Electroweak Interactions and Unified Theories
17 March 2019
Measurement of ttH in Diphoton Final State using 139 fb$^{-1}$ data collected by the ATLAS experiment during the LHC Run-2

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Overview

- The associated production of the Higgs boson with top quarks provides a direct access to the top-Higgs coupling

- The diphoton channel is one of the leading channels in the $tt\bar{H}$ measurements
  - The diphoton resonant decay is an unambiguous signature for the Higgs boson
  - Robust background estimation from diphoton mass sidebands
Photon performance in ATLAS

- Photons are selected using a cut-based multivariate discriminant based on shower shape variables in the EM calorimeter.

- A “tight” identification, typically used in analysis, has an efficiency > 90% for high \( p_T \) photons, and a rejection at \( 10^3 - 10^4 \).
B-tagging performance in ATLAS

- B-jets are tagged using a multivariate discriminant combining tracking, secondary vertex and decay chain information.

- The b-tagging is calibrated with a $\text{tt}\bar{\text{t}}$ control sample.

- In the ttH analysis, a b-tagger with a 77% efficiency is used, corresponding to a rejection of light jet at the level of a few hundreds.
**The diphoton sample in ATLAS**

Select two energetic and well isolated photons

\[ P_{T1}/m_{\gamma\gamma} > 0.4, \quad P_{T2}/m_{\gamma\gamma} > 0.35 \]

\[ |\eta| < 1.37 \text{ or } 1.52 < |\eta| < 2.37 \]

**Quality requirement** - Isolation and identification criteria

\[ \sim 1.5 \text{ million events with } 105 \text{ GeV} < m_{\gamma\gamma} < 160 \text{ GeV at } 139 \text{ fb}^{-1} \]

Assume the theoretical prediction, at **139 fb}^{-1}**, the LHC should have produced

- \(~ \sim 7,000,000\) Higgs bosons
- \(~ \sim 70,000\) via ttH production
- \(~ \sim 160\) in the ttH\(\gamma\gamma\) channel

for the ATLAS experiment
Strategy

Use photons to tag the Higgs Boson

Use jets (b-jets), leptons, and $E_T^{\text{miss}}$ to capture the characteristics of top quarks

Directly use properties of the objects in the event to train a multivariate discriminant
Multivariate Training

Training variables

- 4-momenta of photons, jets, leptons
- Whether or not a jet is b-tagged
- Missing transverse energy and its $\phi$ direction

This discriminant is trained with

- **Signal - Powheg** Monte Carlo that models signal events
- **Background - data control sample** where the photon quality (isolation and/or identification) requirement is reversed
  - Mostly $\gamma\gamma +$ jets events, our main background before selection
  - See Jennet Dickinson’s talk for our understanding of the background composition
**Training variables**

*Some* example training variables

- **Photons**
- **Jets**
- **MET**
- **Leptons**

The training algorithm is a *Boosted Decision Tree (BDT)*
The BDT is trained for events with a lepton (leptonic) and events without a lepton (hadronic), separately.

Events with low BDT scores are removed.

The remaining events are classified into multiple categories with different signal-to-background-ratios (S/Bs) based on the BDT scores, to maximize the sensitivity.
Performance of Categorization

Event yields in a narrow mass window around 125 GeV

<table>
<thead>
<tr>
<th>Category</th>
<th>$t\bar{t}H$ Signal</th>
<th>non-$t\bar{t}H$ Higgs</th>
<th>Continuum Background</th>
<th>Total (Expected)</th>
<th>$\sigma_{68}$ (GeV)</th>
<th>$\sigma_{90}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>'Lep' Category 1</td>
<td>7.9 ± 1.5</td>
<td>0.42 ± 0.12</td>
<td>4.6 ± 0.9</td>
<td>12.9 ± 1.8</td>
<td>1.56</td>
<td>2.80</td>
</tr>
<tr>
<td>'Lep' Category 2</td>
<td>3.9 ± 0.6</td>
<td>0.43 ± 0.15</td>
<td>7.5 ± 1.2</td>
<td>11.8 ± 1.3</td>
<td>1.75</td>
<td>3.13</td>
</tr>
<tr>
<td>'Lep' Category 3</td>
<td>1.45 ± 0.24</td>
<td>0.49 ± 0.19</td>
<td>7.5 ± 1.2</td>
<td>9.5 ± 1.2</td>
<td>1.85</td>
<td>3.30</td>
</tr>
<tr>
<td>'Had' Category 1</td>
<td>6.9 ± 1.6</td>
<td>0.8 ± 0.5</td>
<td>4.5 ± 0.9</td>
<td>12.2 ± 1.9</td>
<td>1.39</td>
<td>2.48</td>
</tr>
<tr>
<td>'Had' Category 2</td>
<td>5.6 ± 1.0</td>
<td>1.1 ± 0.8</td>
<td>16.5 ± 1.7</td>
<td>23.2 ± 2.3</td>
<td>1.58</td>
<td>2.84</td>
</tr>
<tr>
<td>'Had' Category 3</td>
<td>7.7 ± 1.3</td>
<td>3.1 ± 2.2</td>
<td>56.0 ± 3.0</td>
<td>67 ± 4</td>
<td>1.65</td>
<td>2.96</td>
</tr>
<tr>
<td>'Had' Category 4</td>
<td>4.9 ± 0.8</td>
<td>5 ± 4</td>
<td>101 ± 4</td>
<td>111 ± 6</td>
<td>1.67</td>
<td>3.00</td>
</tr>
</tbody>
</table>

- The S/B goes beyond 1 in the best “hadronic” and “leptonic” categories
- Contamination of non-$t\bar{t}H$ Higgs signals are strongly suppressed; $t\bar{t}H$ purity reaches 90% level in the best categories
- Best categories also correspond to categories with best diphoton resolutions
Diphoton mass distributions (hadronic)

**ATLAS Preliminary**
- $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

$m_{\gamma\gamma}$ distribution for different categories:

- **Had 1 category**
  - Data
  - Continuum Background
  - Total Background
  - Signal + Background

- **Had 2 category**
  - Data
  - Continuum Background
  - Total Background
  - Signal + Background

- **Had 3 category**
  - Data
  - Continuum Background
  - Total Background
  - Signal + Background

- **Had 4 category**
  - Data
  - Continuum Background
  - Total Background
  - Signal + Background
Diphoton mass distributions (hadronic)

ATLAS Preliminary
\sqrt{s} = 13 \text{ TeV, 139 fb}^{-1}

\begin{align*}
\text{Events / 1.375 GeV} &
\begin{array}{c}
\hline
\text{Data} \\
\text{Continuum Background} \\
\text{Total Background} \\
\text{Signal + Background} \\
\hline
\end{array}
\end{align*}

m_H = 125.09 \text{ GeV}

Had 1 category
Diphoton mass distributions (hadronic)
Diphoton mass distributions (leptonic)

\[ m_{\gamma\gamma} \text{ [GeV]} \]

Events / 1.375 GeV

Data
Continuum Background
Total Background
Signal + Background

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

Lep 1 category

Lep 2 category

Lep 3 category

\( m_h = 125.09 \text{ GeV} \)

Preliminary
ATLAS

= 13 \text{ TeV, 139 fb}^{-1}

= 125.09 \text{ GeV}

$H_{\text{Lep}}$

\( m_{\gamma\gamma} \text{ [GeV]} \)

\[ m_{\gamma\gamma} \text{ [GeV]} \]

Events / 1.375 GeV

Data
Continuum Background
Total Background
Signal + Background

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

Lep 1 category

Lep 2 category

Lep 3 category

\( m_h = 125.09 \text{ GeV} \)

Preliminary
ATLAS

= 13 \text{ TeV, 139 fb}^{-1}

= 125.09 \text{ GeV}

$H_{\text{Lep}}$
A nice way to visualize the power of categorization is to draw the S/B weighted mass distribution.
Summary of expected and observed event yields

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV, 139 fb}^{-1} \)

<table>
<thead>
<tr>
<th>Events</th>
<th>Data - Bkg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Had 4</td>
<td>100</td>
</tr>
<tr>
<td>Had 3</td>
<td>70</td>
</tr>
<tr>
<td>Had 2</td>
<td>50</td>
</tr>
<tr>
<td>Had 1</td>
<td>30</td>
</tr>
<tr>
<td>Lep 3</td>
<td>20</td>
</tr>
<tr>
<td>Lep 2</td>
<td>10</td>
</tr>
<tr>
<td>Lep 1</td>
<td>5</td>
</tr>
</tbody>
</table>

Data
- \( \ttH (\mu=1.4) \)
- Non-\( \ttH \) Higgs
- Cont. Bkg.

Had categories
- 4 Had
- 3 Had
- 2 Had
- 1 Had

Lep categories
- 3 Lep
- 2 Lep
- 1 Lep

All numbers calculated in a mass window containing 90% of the \( \ttH \) signal events
The expected significance of the ttH process is $4.2 \, \sigma$, the observed is $4.9 \, \sigma$

The measured ttH cross section times $H \rightarrow \gamma\gamma$ branching ratio

\[
\sigma_{t\bar{t}H} \times B_{\gamma\gamma} = 1.59^{+0.43}_{-0.39} \text{ fb} = 1.59^{+0.38}_{-0.36} \text{ (stat.)} \, ^{+0.15}_{-0.12} \text{ (exp.)} \, ^{+0.15}_{-0.11} \text{ (theo.)} \text{ fb}
\]

while the SM expectation is

\[
\sigma_{t\bar{t}H} \times B_{\gamma\gamma} = 1.15^{+0.09}_{-0.12} \text{ fb}
\]
The expected significance of the \( ttH \) process is 4.2 \( \sigma \), the observed is 4.9 \( \sigma \).

The measured \( ttH \) cross section times \( H \right\right\gamma\gamma \) branching ratio is:

\[
\sigma_{ttH} \times B_{\gamma\gamma} = 1.59^{+0.43}_{-0.39} \text{ fb} = 1.59^{+0.38}_{-0.36} \text{ (stat.)} +0.15_{-0.12} \text{ (exp.)} +0.15_{-0.11} \text{ (theo.) fb}
\]

The signal strength (obs/SM) is measured to be:

\[
\mu_{ttH} = 1.38^{+0.41}_{-0.36} = 1.38^{+0.33}_{-0.31} \text{ (stat.)} +0.13_{-0.11} \text{ (exp.)} +0.22_{-0.14} \text{ (theo.)}
\]
## Breakdown of systematic uncertainties

<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><strong>Theory uncertainties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Underlying Event and Parton Shower (UEPS)</td>
<td>5.0</td>
<td>7.2</td>
</tr>
<tr>
<td>Modeling of Heavy Flavor Jets in non-$t\bar{t}H$ Processes</td>
<td>4.0</td>
<td>3.4</td>
</tr>
<tr>
<td>Higher-Order QCD Terms (QCD)</td>
<td>3.3</td>
<td>4.7</td>
</tr>
<tr>
<td>Parton Distribution Function and $\alpha_S$ Scale (PDF+$\alpha_S$)</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<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>
</tr>
<tr>
<td><strong>Experimental uncertainties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photon Energy Resolution (PER)</td>
<td>5.5</td>
<td>6.2</td>
</tr>
<tr>
<td>Photon Energy Scale (PES)</td>
<td>2.8</td>
<td>2.7</td>
</tr>
<tr>
<td>$\text{Jet}/E_T^{\text{miss}}$</td>
<td>2.3</td>
<td>2.7</td>
</tr>
<tr>
<td>Photon Efficiency</td>
<td>1.9</td>
<td>2.7</td>
</tr>
<tr>
<td>Background Modeling</td>
<td>2.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Flavor Tagging</td>
<td>0.9</td>
<td>1.1</td>
</tr>
<tr>
<td>Leptons</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Pileup</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Luminosity and Trigger</td>
<td>1.6</td>
<td>2.3</td>
</tr>
<tr>
<td>Higgs Boson Mass</td>
<td>1.6</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Summary

- ATLAS measurement of the $ttH \rightarrow \gamma\gamma$ process from the full LHC Run-2 data set was reported

- The $ttH$ process is observed in the diphoton decay mode with a significance of 4.9 $\sigma$

- The $ttH$ cross section times $H \rightarrow \gamma\gamma$ branching ratio is measured to be $1.59^{+0.43}_{-0.39}$ fb

- Details are available in ATLAS-CONF-2019-004
Back up
Unweighted diphoton mass distribution

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

$m_H = 125.09$ GeV

All categories
Weighted diphoton mass distribution

\[ m_{\gamma\gamma} \text{ [GeV]} \]

\[ \frac{\text{Sum of Weights}}{1.375 \text{ GeV}} \]

Data, Continuum Background, Total Background, Signal + Background

**ATLAS** Preliminary
\[ \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \]
\[ m_H = 125.09 \text{ GeV} \]

All categories
\[ \ln(1+S/B) \text{ weighted sum} \]
Unweighted diphoton mass distribution

\[ \sqrt{s} = 13 \text{ TeV}, 36.1 - 79.8 \text{ fb}^{-1} \]

- \( \tilde{t}\tilde{t}H (b\bar{b}) \):
  - Total: \( 0.79 \pm 0.61 \)
  - Stat.: \( 0.29 \pm 0.28 \)
  - Syst.: \( 0.53 \pm 0.27 \)

- \( \tilde{t}\tilde{t}H (\text{multilepton}) \):
  - Total: \( 1.56 \pm 0.42 \)
  - Stat.: \( 0.30 \pm 0.29 \)
  - Syst.: \( 0.30 \pm 0.27 \)

- \( \tilde{t}\tilde{t}H (\gamma\gamma) \):
  - Total: \( 1.39 \pm 0.48 \)
  - Stat.: \( 0.42 \pm 0.38 \)
  - Syst.: \( 0.23 \pm 0.17 \)

- \( \tilde{t}\tilde{t}H (ZZ) \):
  - Total: \( < 1.77 \text{ at } 68\% \text{ CL} \)

- Combined:
  - Total: \( 1.32 \pm 0.28 \)
  - Stat.: \( 0.18 \pm 0.21 \)
  - Syst.: \( 0.21 \pm 0.19 \)