Search for the Higgs boson decay to a pair of muons with 139 fb$^{-1}$ at the ATLAS detector at the LHC

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on behalf of the ATLAS Collaboration

Higgs Hunting
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Paris, France
Motivation

Higgs discovery in 2012 a major triumph of the Standard Model

Observed in main production modes and many decay channels

H->\mu\mu has sensitivity to coupling to second generation fermions

This talk: H->\mu\mu with full Run 2 ATLAS dataset

ATLAS-CONF-2019-028
Key difficulty

small signal yield

(~1300 expected events before selection in 139 fb⁻¹)

large DY background

very small S/B

(~1/500 inclusive)

-> keep as much signal as possible
-> require excellent background modelling

Top figure from CERN Yellow Report 4, bottom from ATLAS-CONF-2019-028
Strategy

Loose muon and event selection

Fully-multivariate categorisation to maximise sensitivity

Fit the dimuon invariant mass in data
Object and Event Selection

**MUON**
- Loose quality muons
- Loose isolation
  - $|\eta| < 2.7$, $p_T > 15$ GeV

**JET**
- $|\eta| < 4.5$, $p_T > 25$ (30) GeV for $|\eta| < 2.4$ (otherwise)
- Pileup reduction cuts
- Loosest b-tagging (for the veto)

**EVENT**
- Loosest unprescaled single-µ triggers
- 2 opposite charge muons, lead muon $p_T > 27$ GeV
- Veto events with b-tagged jet(s)
- Recover FSR to improve mass resolution
<table>
<thead>
<tr>
<th>jet channel</th>
<th>XGBoost discriminant(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-jet</td>
<td>Higgs classifier (3 categories)</td>
</tr>
<tr>
<td>1-jet</td>
<td>Higgs classifier (3 categories)</td>
</tr>
<tr>
<td>$\geq$ 2-jet</td>
<td>VBF clf. (3 categ.), if not VBF: Higgs clf. (3 categ.)</td>
</tr>
</tbody>
</table>

**Higgs classifier**: ggF + VBF signal MC trained against data sidebands*

**VBF classifier**: VBF signal MC trained against data sidebands

*data sidebands: 2015-2018, $m_{\mu\mu} \in [110, 120] \cup [130, 180]$ GeV
Training variables

jet channel   Training variables

0-jet          \( p_T^{\mu\mu}, Y_{\mu\mu}, |\cos(\theta^*)| \)
1-jet          0-jet variables + \( p_T^{j1}, \eta_{j1}, \Delta \phi_{j1,\mu\mu} \)
\( \geq 2 \)-jet 1-jet variables + \( p_T^{j2}, \eta_{j2}, \Delta \phi_{j2,\mu\mu}, p_T^{jj}, Y_{jj}, \Delta \phi_{jj,\mu\mu}, m_{jj}, \text{MET} \)

Figures from ATLAS-CONF-2019-028
Categorisation summary

$S = \# \text{ signal events}$

$B = \# \text{ background events}$

(both $m_{\mu\mu} \in [120, 130] \text{ GeV}$)

**Signal composition**

**Background composition**

Category boundaries determined by optimising the number counting significance

Figure from ATLAS-CONF-2019-028
Background modelling: key challenge

TRUE BACKGROUND
BACKGROUND MODEL
SPURIOUS SIGNAL (SS)
"TRUE BACKGROUND"

TRUE BACKGROUND
BACKGROUND MODEL
SPURIOUS SIGNAL

# events

m\mu\mu
Very high-statistics MC needed to validate the background model. Dedicated **fast DY simulation with parametrised response.**

Event generation (DY only)
NLO Powheg (0 and 1 jet) and LO Alpgen (2 jet) fast event generation (~100 ab\(^{-1}\))

Muon corrections
Parametrised smearing for \(p_T\), derived from full-sim.
Reco+ID, isolation, impact parameter efficiencies derived from full-sim.
Trigger efficiencies from measurements in data.

+ Jet \(p_T\) corrections + FSR resolution + Pileup jet overlay + MET smearing

Normalisation adjusted to data.
BACKGROUND MODEL

TRUE BACKGROUND
BACKGROUND MODEL
SPURIOUS SIGNAL

# events vs. \(m\mu\mu\)
PDF_{bkg}(m_{\mu\mu}) = \textbf{Rigid core } \times \textbf{Empirical function}

<table>
<thead>
<tr>
<th>Common to all categories</th>
<th>Different in each category*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid, physics-inspired shape. Analytic LO $2\rightarrow 2$ Drell-Yan lineshape, convolved to model muon resolution.</td>
<td>Flexible analytical function. Models remaining part of the spectrum.</td>
</tr>
</tbody>
</table>
Double-sided Crystal Ball function

**ATLAS** Simulation Preliminary

$\sqrt{s}=13$ TeV, $H \rightarrow \mu\mu$

VBF High

- $m_{\text{CB}}^0 = 124.7$ GeV
- $\sigma_{\text{CB}} = 3.0$ GeV

0-jet High

- $m_{\text{CB}}^0 = 124.8$ GeV
- $\sigma_{\text{CB}} = 2.6$ GeV

FSR tail recovered

Figure from ATLAS-CONF-2019-028
Example fit to data (VBF High)

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

VBF High

- Data
- Total PDF
- Signal PDF
- Bkg. PDF

Figure from ATLAS-CONF-2019-028
Uncertainties

Statistics dominated analysis (~0.7)
Systematics ~0.1

Systematic uncertainties sources:

1) Spurious signal (background mismodelling)
2) Signal acceptance (theoretical and experimental)
Results

~50% improvement w.r.t. previous ATLAS result

Significance: $0.8\sigma$ (1.5$\sigma$ expected)

Measurement: $\mu = 0.5 \pm 0.7$

Limit (95% CL): $1.7 \times \text{SM}$ (1.3 expected B-only, 2.2 SM S+B)
Summary

Search for SM Higgs boson decay to muon pairs

Loose muon and event selection
Optimised multivariate categorisation
Improved background modelling

$0.8\sigma$ ($1.5\sigma$ expected)
ATLAS Preliminary

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

H \rightarrow \mu\mu

log(1+S/B) weighted

Data - Bkg.
Event Display

Run 281411, Event 312600026
Time 2015-10-11, 18:48 CEST

\( m(\mu, \mu) = 124 \text{ GeV} \)
\( m(\text{jet, jet}) = 1237 \text{ GeV} \)
Observed Summary

Expected

<table>
<thead>
<tr>
<th>ATLAS Simulation Preliminary</th>
<th>Total</th>
<th>Stat.</th>
<th>Syst.</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → μμ, √s = 13 TeV, 139 fb⁻¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VBF High</td>
<td>1.0 ± 1.5 (± 1.5, ± 0.4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VBF Medium</td>
<td>1.0 ± 0.7 (± 0.9, ± 0.3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VBF Low</td>
<td>1.0 ± 0.7 (± 0.9, ± 0.3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-jet High</td>
<td>1.0 ± 2.0 (± 2.0, ± 0.5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-jet Medium</td>
<td>1.0 ± 2.0 (± 2.0, ± 0.5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-jet Low</td>
<td>1.0 ± 4.1 (± 4.0, ± 0.9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-jet High</td>
<td>1.0 ± 2.1 (± 2.1, ± 0.8)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-jet Medium</td>
<td>1.0 ± 2.1 (± 2.1, ± 0.8)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-jet Low</td>
<td>1.0 ± 3.0 (± 3.0, ± 0.5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-jet High</td>
<td>1.0 ± 2.3 (± 2.2, ± 0.5)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0-jet Medium</td>
<td>1.0 ± 2.6 (± 2.6, ± 0.6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-jet Low</td>
<td>1.0 ± 4.2 (± 4.1, ± 0.9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined</td>
<td>1.0 ± 0.7 (± 0.7, ± 0.2)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total Stat. Syst. SM

ATLAS Simulation Preliminary

H → μμ, √s = 13 TeV, 139 fb⁻¹

Expected

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td>H → μμ, √s = 13 TeV, 139 fb⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VBF High</td>
<td>0.5 ± 1.4 (± 1.4, ± 0.2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VBF Medium</td>
<td>4.1 ± 2.4 (± 2.4, ± 0.6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VBF Low</td>
<td>4.8 ± 2.9 (± 2.9, ± 0.6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-jet High</td>
<td>-2.7 ± 2.0 (± 2.0, ± 0.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-jet Medium</td>
<td>1.3 ± 2.6 (± 2.6, ± 0.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-jet Low</td>
<td>-5.8 ± 4.1 (± 4.1, ± 1.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-jet High</td>
<td>0.6 ± 2.1 (± 2.1, ± 0.4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-jet Medium</td>
<td>0.9 ± 2.1 (± 2.1, ± 0.4)</td>
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<td></td>
</tr>
<tr>
<td>1-jet Low</td>
<td>-2.6 ± 3.1 (± 3.1, ± 0.9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-jet High</td>
<td>-0.9 ± 2.3 (± 2.3, ± 0.9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-jet Medium</td>
<td>1.3 ± 2.6 (± 2.6, ± 0.6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-jet Low</td>
<td>5.0 ± 4.2 (± 4.2, ± 1.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined</td>
<td>0.5 ± 0.7 (± 0.7, ± 0.2)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total Stat. Syst. SM

Figures from ATLAS-CONF-2019-028
Summary

Unweighted

Weighted

Figures from ATLAS-CONF-2019-028
Final state radiation

Muons can lose energy via radiating a photon:
- $\rightarrow$ adding the photon to $m_{\mu\mu}$ calculation improves resolution

Only events with FSR

All events

Figures from ATLAS-CONF-2019-028
Selected empirical functions

<table>
<thead>
<tr>
<th>Category</th>
<th>Empirical Function</th>
<th>$\text{max}(SS/\delta S)[%]$</th>
<th>$\text{max}(SS/S_{SM})[%]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF High</td>
<td>Power0</td>
<td>10.6</td>
<td>14.7</td>
</tr>
<tr>
<td>VBF Medium</td>
<td>Epoly2</td>
<td>0.51</td>
<td>1.3</td>
</tr>
<tr>
<td>VBF Low</td>
<td>Power1</td>
<td>3.6</td>
<td>7.5</td>
</tr>
<tr>
<td>2-jet High</td>
<td>Epoly2</td>
<td>8.7</td>
<td>16.3</td>
</tr>
<tr>
<td>2-jet Medium</td>
<td>Epoly4</td>
<td>1.2</td>
<td>3.9</td>
</tr>
<tr>
<td>2-jet Low</td>
<td>Epoly3</td>
<td>-8.2</td>
<td>-33.2</td>
</tr>
<tr>
<td>1-jet High</td>
<td>Power1</td>
<td>6.1</td>
<td>12.1</td>
</tr>
<tr>
<td>1-jet Medium</td>
<td>Epoly3</td>
<td>-8.1</td>
<td>-19.8</td>
</tr>
<tr>
<td>1-jet Low</td>
<td>Epoly3</td>
<td>-2.5</td>
<td>-5.8</td>
</tr>
<tr>
<td>0-jet High</td>
<td>Power1</td>
<td>14.6</td>
<td>26.5</td>
</tr>
<tr>
<td>0-jet Medium</td>
<td>Epoly3</td>
<td>-11.6</td>
<td>-39.0</td>
</tr>
<tr>
<td>0-jet Low</td>
<td>Epoly3</td>
<td>-18.5</td>
<td>-74.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Function</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>PowerN</td>
<td>$m_{\mu\mu}^{(a_0+a_1m_{\mu\mu}+a_2m_{\mu\mu}^2+...+a_Nm_{\mu\mu}^N)}$</td>
</tr>
<tr>
<td>EpolyN</td>
<td>$\exp(a_1m_{\mu\mu}+a_2m_{\mu\mu}^2+...+a_Nm_{\mu\mu}^N)$</td>
</tr>
</tbody>
</table>

Tables from ATLAS-CONF-2019-028
## Category yields

<table>
<thead>
<tr>
<th>Category</th>
<th>Data</th>
<th>$S_{SM}$</th>
<th>$S$</th>
<th>$B$</th>
<th>$S/\sqrt{B}$</th>
<th>$S/B$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF High</td>
<td>40</td>
<td>4.5</td>
<td>2.3</td>
<td>34</td>
<td>0.39</td>
<td>6.6</td>
</tr>
<tr>
<td>VBF Medium</td>
<td>109</td>
<td>5.5</td>
<td>2.8</td>
<td>100</td>
<td>0.28</td>
<td>2.8</td>
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<tr>
<td>VBF Low</td>
<td>450</td>
<td>9.6</td>
<td>4.9</td>
<td>420</td>
<td>0.24</td>
<td>1.2</td>
</tr>
<tr>
<td>2-jet High</td>
<td>3400</td>
<td>38</td>
<td>19</td>
<td>3440</td>
<td>0.33</td>
<td>0.6</td>
</tr>
<tr>
<td>2-jet Medium</td>
<td>13938</td>
<td>70</td>
<td>35</td>
<td>13910</td>
<td>0.30</td>
<td>0.3</td>
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<tr>
<td>2-jet Low</td>
<td>40747</td>
<td>75</td>
<td>38</td>
<td>40860</td>
<td>0.19</td>
<td>0.1</td>
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<tr>
<td>1-jet High</td>
<td>2885</td>
<td>32</td>
<td>16</td>
<td>2830</td>
<td>0.31</td>
<td>0.6</td>
</tr>
<tr>
<td>1-jet Medium</td>
<td>24919</td>
<td>107</td>
<td>54</td>
<td>24890</td>
<td>0.35</td>
<td>0.2</td>
</tr>
<tr>
<td>1-jet Low</td>
<td>77482</td>
<td>134</td>
<td>68</td>
<td>77670</td>
<td>0.24</td>
<td>0.1</td>
</tr>
<tr>
<td>0-jet High</td>
<td>24777</td>
<td>85</td>
<td>43</td>
<td>24740</td>
<td>0.27</td>
<td>0.2</td>
</tr>
<tr>
<td>0-jet Medium</td>
<td>85281</td>
<td>155</td>
<td>79</td>
<td>85000</td>
<td>0.27</td>
<td>0.1</td>
</tr>
<tr>
<td>0-jet Low</td>
<td>180478</td>
<td>144</td>
<td>73</td>
<td>180000</td>
<td>0.17</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

Table from ATLAS-CONF-2019-028
Background model selection

For each category:

A) Re-weight the fast MC to data sidebands:
   1. 1st order polynomial in VBF categories
   2. 2nd order polynomial in Higgs categories

B) Pick the Empirical function based on these criteria:
   1. Goodness of B-only fits: $P(\chi^2) > 1\%$
      1. Data sidebands
      2. Full-sim MC: DY (Sherpa), top, diboson
      3. Re-weighted fast MC
   2. $\text{SS}/\sigma_S < 20\%$
      1. $\text{SS}$ is the spurious signal (maximum over [120, 130] GeV range) obtained in S+B fits to re-weighted fast MC
      2. $\sigma_S$ is the statistical uncertainty on the extracted signal at 139fb$^{-1}$
   3. Smallest number of parameters
   4. Smallest SS value

Both adjust normalisation
Full Object Selection

1) **Muons**
   - Loose muon Working Point
   - FixedCutPflowLoose isolation
   - $p_T > 15 \text{ GeV}$
   - $|\eta| < 2.7$
   - impact parameters: $|d_0 \text{ significance}| < 3.0, |z_0 \sin(\theta)| < 0.5 \text{ mm}$

2) **Jets**
   - Antikt4TopoEM algorithm
   - $|\eta| < 4.5$
   - $p_T > 25 \text{ GeV}$ for $|\eta| < 2.4$
   - $p_T > 30 \text{ GeV}$ for $2.4 < |\eta| < 4.5$
   - JetVertexTagging $> 0.59$ for $(p_T < 60 \text{ GeV} \&\& |\eta| < 2.4)$
   - $fJVT < 0.5$ forward region
   - pass MV2c10 60% WP for $(|\eta| < 2.5 \&\& p_T > 20 \text{ GeV})$. Only used for the b-veto purpose.

3) **Electrons (only used for overlap removal)**
   - *Medium* likelihood, $p_T > 7 \text{ GeV}$, $|\eta| < 2.47$ excluding the crack region
   - *Loose* isolation
   - impact parameters: $|d_0 \text{ significance}| < 3.0, |z_0 \sin(\theta)| < 0.5 \text{ mm}$
Full Event Selection

- Pass GRL and event cleaning for data
- Pass lowest unprescaled single muon trigger
- Trigger matching
- Two opposite sign muons
- Lead muon $p_T > 27$ GeV
- Subleading muon $p_T > 15$ GeV
- Veto events with a b-jet