Higgs Results from ATLAS

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On behalf of ATLAS collaboration

Rencontres de Moriond
QCD and High Energy Interactions
La Thuile, March 25th - April 1st, 2017
After the historical discovery of the new particle (125 GeV) in 2012 and its consistency with the SM Higgs boson, an extensive and rich research program has been established:

- measurements of its properties, study of rare decays
- searches beyond the Standard Model (BSM)
- Using the Higgs boson as a tool for discovery

Latest published results from ATLAS with a subset of Run2 dataset corresponding to 13-15 fb⁻¹

- a couple of selected topics will be shown

New results with full 2015+2016 dataset (L=36.1 fb⁻¹)

- $H \rightarrow \gamma\gamma$ + missing transverse energy signatures
- $H \rightarrow \mu\mu$ decays

Full list of results [https://twiki.cern.ch/twiki/bin/view/AtlasPublic](https://twiki.cern.ch/twiki/bin/view/AtlasPublic)
LHC and ATLAS performance

- Excellent LHC performance in 2016
  - more data than all other years combined!
  - Peak $L = 1.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (exceeded design)
  - higher pileup conditions

- ATLAS:
  - High data taking efficiency (>92%) and data quality efficiency (93-95%)

<table>
<thead>
<tr>
<th>Ecm</th>
<th>Year</th>
<th>Luminosity used in analyses</th>
<th>Uncertainty on luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{7}$ TeV</td>
<td>2011</td>
<td>4.5 fb$^{-1}$</td>
<td>1.8% final</td>
</tr>
<tr>
<td>$\sqrt{8}$ TeV</td>
<td>2012</td>
<td>20.3 fb$^{-1}$</td>
<td>2.8% final</td>
</tr>
<tr>
<td>$\sqrt{13}$ TeV</td>
<td>2015</td>
<td>3.2 fb$^{-1}$</td>
<td>2.1% final</td>
</tr>
<tr>
<td>$\sqrt{13}$ TeV</td>
<td>2016</td>
<td>32.9 fb$^{-1}$</td>
<td>3.2% prel</td>
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New
H(125 GeV) production and decays

From 8 to 13 TeV
- $$\sigma(H)$$ increased by (~2.5)
- ttH increased by (~4)

Theory progress: (e.g. N3LO inclusive ggF cross section, NNLO differential cross section, updated PDF4LHC)
Run1 legacy

Studies / measurements of properties

- Angular distributions showed consistency with a particle of spin 0 and even parity
- All measured processes in agreement with SM within 2 standard deviations
- Largest deviation in measured ttH cross section

From ATLAS+CMS combination production modes

- observation of ggF, VBF
- evidence for VH and ttH!

decay modes

- observation of H→γγ, ZZ, WW
- observation of H→ττ

Mass within 0.2% precision $m_H = 125.09 \pm 0.24$ GeV
Flash some of the latest published results with $s L=13-15 fb^{-1}$

$H \rightarrow \gamma\gamma$

$H \rightarrow ZZ^* \rightarrow 4l, l=e,\mu$

Combination

$H \rightarrow \gamma\gamma, ZZ^*$
\( H(125) \rightarrow \gamma\gamma \)

- High resolution channel, rare decay 0.2%
- Narrow resonance on top of background
  - \( \gamma\gamma, \gamma\text{-jet}, \text{jet-jet} \)
- Event categorization to probe production modes and kinematic properties
- Signal extracted by fit of \( m_{\gamma\gamma} \) spectrum
  - **Observed Significance 4.7 \( \sigma \)**

Extract fiducial and differential cross-section \( P_{T\gamma\gamma} \): data & theory overall good agreement

Signal strength per production mode
No significant deviation from SM observed
$H(125) \rightarrow ZZ^* \rightarrow (4l), l=e,\mu$
H(125) \rightarrow ZZ^* \rightarrow (4l), l=e,\mu

selection for fiducial cross section

<table>
<thead>
<tr>
<th>Lepton definition</th>
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<tbody>
<tr>
<td>Muons: $p_T &gt; 5$ GeV, $</td>
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<table>
<thead>
<tr>
<th>Pairing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading pair: SFOS lepton pair with smallest $</td>
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<tr>
<td>Sub-leading pair: Remaining SFOS lepton pair with smallest $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Event selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton kinematics: Leading leptons $p_T &gt; 20, 15, 10$ GeV</td>
</tr>
<tr>
<td>Mass requirements: $50 &lt; m_{12} &lt; 106$ GeV; $12 &lt; m_{34} &lt; 115$ GeV</td>
</tr>
<tr>
<td>Lepton separation: $\Delta R(\ell_i, \ell_j) &gt; 0.1(0.2)$ for same(opposite)-flavour leptons</td>
</tr>
<tr>
<td>$J/\psi$ veto: $m(\ell_i, \ell_j) &gt; 5$ GeV for all SFOS lepton pairs</td>
</tr>
<tr>
<td>Mass window: $115 &lt; m_{4\ell} &lt; 130$ GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Final state</th>
<th>measured $\sigma_{\text{fid}}$ [fb]</th>
<th>$\sigma_{\text{fid,SM}}$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4\mu$</td>
<td>1.28 $^{+0.48}_{-0.40}$</td>
<td>0.93 $^{+0.06}_{-0.08}$</td>
</tr>
<tr>
<td>$4e$</td>
<td>0.81 $^{+0.51}_{-0.38}$</td>
<td>0.73 $^{+0.05}_{-0.06}$</td>
</tr>
<tr>
<td>$2\mu2e$</td>
<td>1.29 $^{+0.58}_{-0.46}$</td>
<td>0.67 $^{+0.04}_{-0.04}$</td>
</tr>
<tr>
<td>$2e2\mu$</td>
<td>1.10 $^{+0.49}_{-0.40}$</td>
<td>0.76 $^{+0.05}_{-0.06}$</td>
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</table>

Measured cross sections and couplings consistent with SM within 2$\sigma$
H(125): ZZ* + γγ combination

Best fit cross-section per production mechanism

<table>
<thead>
<tr>
<th></th>
<th>Best fit value (pb)</th>
<th>SM prediction (pb)</th>
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<tbody>
<tr>
<td>σ_{ggF}</td>
<td>47.8^{+9.8}_{-9.4}</td>
<td>44.5 ± 2.3</td>
</tr>
<tr>
<td>σ_{VBF}</td>
<td>7.9^{+2.8}_{-2.4}</td>
<td>3.52 ± 0.07</td>
</tr>
<tr>
<td>σ_{VHhad}</td>
<td>-2.5^{+2.9}_{-2.6}</td>
<td>1.36 ± 0.03</td>
</tr>
<tr>
<td>σ_{VHlep}</td>
<td>0.32^{+1.07}_{-0.79}</td>
<td>0.64 ± 0.02</td>
</tr>
<tr>
<td>σ_{top}</td>
<td>-0.11^{+0.67}_{-0.54}</td>
<td>0.60 ± 0.06</td>
</tr>
</tbody>
</table>

Total cross-section: Extrapolate fiducial cross section to full phase space

Cross section consistent with N3LO QCD calculations and NLO EW corrections

\[ \sqrt{s} = 13 \text{ TeV}: \]
\[ \sigma(pp \rightarrow H + X) = 59.0^{+9.7}_{-9.2} \text{(stat)}^{+4.4}_{-3.5} \text{(syst)} \text{pb} \] (ATLAS)
\[ \sigma(pp \rightarrow H + X) = 55.5^{+2.4}_{-3.4} \text{pb} \] (N3LO theory)
Two new results with full 2015+2016 dataset $L=36.1 \text{ fb}^{-1}$

- $H \rightarrow \gamma\gamma$ + MET signatures
- $H \rightarrow \mu\mu$
**H → γγ + E_T^{miss} search**

**Searches for new phenomena (Dark Matter) with H(125) → γγ and E_T^{miss} signature**

3 models considered:

1. **Z' model**
   - DM coupling to H and Z'
   - DM coupling to pseudo-scalar A^0
   - Harder spectrum on E_T^{miss}

2. **Z' 2HDM model**
   - Produced via ggF effective coupling to DM and SM Higgs

3. **Heavy scalar**
   - Z'-2HDM, Dirac DM
   - Z'-2HDM, Scalar DM

**Backgrounds:**
- γγ (dominant), γ+jets, Vγ, Vγγ
- SM Higgs, VH irreducible

**Discriminating variables:**
- E_T^{miss} significance
- Z_{PV}^{γγ} − Z_{PV}^{hard}
- P_T^{γγ}, P_T^{hard}

**Magnitude of vectorial sum of photons and jets**

Data / MC = 200 GeV
A_m = 1 TeV, Z' = 100 GeV, χ = 200 GeV
B Z' = 1 GeV, χ = 275 GeV
H = 60 GeV, χ = 200 GeV
1. Event categorization to increase the sensitivity
   - Five categories determined
2. Signal and background fits per category
   - Signal: Double sided Crystal Ball
   - Background: Exponential
   - Modeling bias associated to selected functional form estimated on MC
3. Results: unbinned fit to $m_{\gamma\gamma}$ spectrum
   - Heavy scalar model: simultaneous fit all categories
   - DM models: fit to Mono-Higgs category
No significant excess beyond SM observed $\rightarrow$ 95% CL limits

1D upper limit for all models

DM simplified models: 2D contour limits

**Simplified models:**
- Strong 1D upper limits on the DM production
- 2D limits contour on signal strength for both types of the simplified models

**Heavy scalar:**
- Strong upper limits on the heavy scalar production with mass 250-360 GeV
$H \rightarrow \mu\mu$ decays

Motivation:
- Sensitive channel to measure Higgs couplings to second generation fermions

Characteristics of the channel:
- Clean experimental signature, small BR $\sim 2.18 \times 10^{-4}$
- Dominant background: Drell Yan $Z/\gamma^* \rightarrow \mu\mu$

Analysis strategy:
- Event classification in orthogonal categories for ggF and VBF production
  - Distinguish VBF characteristics by using discriminating variables in a BDT
  - ggF categories based on $\eta$, $P_T^{\mu\mu}$
- Fit dimuon spectra (very good signal resolution, smooth $m_{\mu\mu}$ around $m_H$)
  - Simultaneous fit to the observed $m_{\mu\mu}$ in all categories ($110 \text{ GeV} < m_{\mu\mu} < 160 \text{ GeV}$) to extract signal strength and determine background normalization and shapes
Muon performance

**Muon efficiency versus $p_T$**

**Di-muon invariant mass resolution versus $\eta$**

**Signal model fit in low $p_T^{\mu\mu}$ category**

**Signal model fit in high $p_T^{\mu\mu}$ category**

[ATLAS Simulation Preliminary]

Central low $p_T^{\mu\mu}$

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

FWHM=5.6 GeV

[ATLAS Simulation Preliminary]

Central high $p_T^{\mu\mu}$

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

FWHM=6.3 GeV

[ggF $H(125) \rightarrow \mu\mu$]

Entries / 0.5 GeV

$0.2$ $0.4$ $0.6$ $0.8$ $1$ $1.2$ $1.4$

$110$ $115$ $120$ $125$ $130$ $135$ $140$

[ggF $H(125) \rightarrow \mu\mu$]

Entries / 0.5 GeV

$0.2$ $0.4$ $0.6$ $0.8$ $1$ $1.2$ $1.4$ $1.6$

$110$ $115$ $120$ $125$ $130$ $135$ $140$

[ATLAS Simulation Preliminary]

$\mu\mu$ invariant mass resolution versus $\eta$

[ATLAS Simulation Preliminary]

$\mu\mu$ invariant mass resolution versus $\eta$

[ATLAS Simulation Preliminary]

$\mu\mu$ efficiency versus $p_T$
H → μμ decays


<table>
<thead>
<tr>
<th>Data set</th>
<th>Upper Limit @95 C.L</th>
<th>Signal Strength μs</th>
</tr>
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<tbody>
<tr>
<td>Run2 (13 TeV)</td>
<td>3.0 (3.1)</td>
<td>-0.07 ± 1.5</td>
</tr>
<tr>
<td>Run1+Run2 (7+8+13 TeV)</td>
<td>2.7 (2.8)</td>
<td>-0.13 ± 1.4</td>
</tr>
</tbody>
</table>
Summary / Conclusions

- ATLAS in full speed to prepare the final publications on Higgs searches with the full dataset available from 2015+2016 @13 TeV

- Two new analyses presented in this talk
  - $H \rightarrow \mu \mu, H \rightarrow \gamma \gamma + E_T^{\text{miss}}$
  - No significant excess w.r.t SM observed
  - Improved limits w.r.t. Run1 or previous Run2 results

- Many more analyses in preparation, coming soon
  - Stay tuned
BACKUP
H→γγ + E_T^{miss} search

90% CL Z'_B limits reinterpreted as DM-nucleon scattering cross section as a function of DM mass, for a spin-independent scenario

90% CL Z'_B

ATLAS Preliminary

ATLAS: pp → h(γγ) + χ χ, Z'_B, Dirac DM

sinθ = 0.3, g_q = 1/3, g_χ = 1

√s = 13 TeV, 36.1 fb^{-1}

Preliminary

Spin-independent

DM mass m_χ [GeV]

DM-nucleon cross section [cm^2]

1 \text{GeV} \leq m_χ \leq 10^3 \text{GeV}
Run2 studies

Exploring the higher energy regime and increased statistics in Run2 and the progress from the theory side

1. Measuring Higgs boson properties @13 TeV (indirect search for new physics)
   - decays to bosons: $H \rightarrow \gamma\gamma, ZZ^*, WW^*$
     - Access to all production modes
     - Study of BEH kinematics, spin/parity properties, improve mass measurement, width studies
     - Access to rare decays $H \rightarrow Z\gamma$
   - Decays to fermions: $H \rightarrow \mu\mu, bb, \tau\tau$
     - Study of Yukawa couplings to quarks and leptons
     - Challenging either to large background (bb, $\tau\tau$ channels) or to tiny BR ($\mu\mu$)
   - ttH production mode search
     - Unique channel to study directly the top Yukawa coupling
     - Profit from the increased cross section @13 TeV
   - Use of H as a tool for new physics
     - (example Dark Matter search $H \rightarrow \gamma\gamma + E_T^{miss}$)

2. BSM studies (direct search for new physics)
   - Many models are studied 2HDM, MSSM in order to understand the Higgs sector, assuming additional Higgs bosons neutral or charged decaying to bosons or fermions
H → μμ: previous ATLAS results

Run1: √8TeV

ATLAS Preliminary

95% CL

Observed (expected) limit = **9.8 (8.2) x SM**


Run2 with L = 13 fb⁻¹

ATLAS Preliminary

95% CL

Observed (expected) limit = **4.4 (5.5) x SM**

The background model fits to the $m_{\mu\mu}$ distribution in different categories. Signal is scaled $\times$ 20.