Measurement of the Higgs Boson Mass

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Seoul
The Higgs Boson Mass

- Free parameter of the SM
- Important ingredient in SM (and BSM) predictions
  - Not a test for new physics, but needed for such tests
  - Previously measured by ATLAS to precision of 0.33%
- Analysis results shown here from arXiv:1806.00242 [hep-ex] (submitted to PLB) except where noted

**Figure:**
- 68% and 95% CL contours
- Fit w/o $M_W$ and $m_t$ measurements
- Fit w/o $M_W$, $m_t$, and $M_H$ measurements
- Direct $M_W$ and $m_t$ measurements

**Table:**
<table>
<thead>
<tr>
<th>$M_W$ (GeV)</th>
<th>$m_t$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.013$</td>
<td>$80.379$</td>
</tr>
</tbody>
</table>

**Equations:**
- $\sigma_{1\pm\text{comb.}} = 0.46\text{ GeV}$
- $m_t = 172.47\text{ GeV}$
- $m_t = 0.46\text{ GeV}$
- $M_W = 80.379 \pm 0.013\text{ GeV}$
- $M_W = 80.25\text{ GeV}$
- $M_W = 80.3\text{ GeV}$
- $M_W = 80.35\text{ GeV}$
- $M_W = 80.4\text{ GeV}$
- $M_W = 80.45\text{ GeV}$
- $M_W = 80.5\text{ GeV}$
- $H = 50\text{ GeV}$
- $H = 300\text{ GeV}$
- $H = 600\text{ GeV}$

**Reference:**
ATLAS in Run-2

• Results shown use 36.1 fb$^{-1}$ of $\sqrt{s}=13$ TeV data collected by ATLAS in 2015 and 2016

• ATLAS is improved compared to Run-1
  ▶ New pixel layer close to beamline improves rejection of electron backgrounds
  ▶ Improved MS coverage for better muon reconstruction efficiency
Precision Mass Measurement

- Measurement involves fitting $m_H$-dependent model to data
  - Model developed from simulation
- Requires precise understanding of particle response in the detector
  - Simulation must accurately reflect data
  - Mass resolution limited by resolution of Higgs boson decay products
Measuring Muon Momenta

• Muon tracks are measured separately in MS and ID
  ▷ Then combined fit w/all hits + calo information
• Resolution and $p_T$ scale measured in Z, J/$\psi$ decays
  ▷ Simulated momenta corrected and smeared to match data
  ▷ Uncertainties on scale <0.05% in barrel, <0.2% in endcap
    ‣ Energy loss, material, radial distortions, B-field
  ▷ Uncertainties on resolution 1-2% in barrel, up to 10% in endcap
• Additional $\eta$-$\phi$ dependent correction for residual ID misalignment improves $Z\rightarrow\mu\mu$ resolution by 1-5%
Electron and Photon Energy Measurement

• For both, reconstruction starts with a cluster in the EM calorimeter
  ▶ Can be matched to track, conversion vertex, or nothing
• MVA calibration for e/γ energy
  ▶ Trained on MC samples
  ▶ Corrects for energy loss in material in front of calorimeter, punch-through, shower leakage, and variation of cluster response
  ▶ Different corrections for electrons, converted photons, and photons
• Energy scale and resolution corrections
  ▶ Z→ee decays used for final determination of resolution and scale
    ✦ Data energy scale corrected to match MC
    ✦ MC resolution corrected to match data
  ▶ Uncertainty on scale<0.1% for e, few per mille for γ
    ✦ From relative calibration of calo layers, material, energy response linearity, and e-γ shower shape differences

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Scale correction parameter $\alpha$

ATLAS Preliminary
\[
\sqrt{s} = 13 \text{ TeV}, \quad L = 3.2 \text{ (2015)} + 32.9 \text{ (2016) fb}^{-1}
\]

- Electrons from Z→ee, 2015 data
- Electrons from Z→ee, 2016 data

Resolution correction $c'$

ATLAS Preliminary
\[
\sqrt{s} = 13 \text{ TeV}, \quad L = 3.2 \text{ (2015)} + 32.9 \text{ (2016) fb}^{-1}
\]

- Electrons from Z→ee

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**Main background is ZZ* production**

- $qq\rightarrow ZZ$ simulated at NLO with POWHEG, QCD+EW corrections as function of $m_{ZZ}$.  
- $gg\rightarrow ZZ$ simulated at LO with $gg2VV$, with k-factor for higher-order QCD effects

**Reducible background from Z+jets and ttbar estimated using data-driven methods**

- Loose lepton isolation and identification requirements imposed
- Electrons and muons accepted down to $p_T$ of 7 and 5 GeV respectively

**Use 4l vertexing constraint in event selection.**

**FSR photons are identified and included in the mass calculation**
Per-Event Response Method

• Less susceptible to statistical fluctuations seen in low-stats measurements like this one
• Response of each $e$ or $\mu$ in each $\eta$-E detector region modeled as sum of 3 gaussians
  ‣ By fit to simulation
  ‣ $3 \sim$ the core and radiative/bremsstrahlung tails
• To obtain 4l response, convolute responses of the 4 leptons
  ‣ Gives 81 gaussians; merged to 4 without losing meaningful information
• PDF for given event obtained by convoluting 4l response with Breit-Wigner
  ‣ Final PDF is convolution of each event’s PDF
• Method validated on $Z \rightarrow 4l$ events

$= P(m_{4l}; m_H, \Gamma_H, \text{kinematics})$
Mass Measurement

- $m_{12}$ kinematically constrained to $m_Z$ to improve the resolution (by ~15%)
- Data in $110 < m_{4l,constrained} < 135$ GeV split by final state ($4\mu$, $2\mu 2e$, $2e2\mu$, $4e$)
  - Resolution better for $\mu$ than $e \rightarrow \sim$ resolution bins
- Each final state is split into 4 bins using BDT trained to separate ggH and ZZ$^*$
  - Gain 8% improvement in uncertainty thanks to improved significance
- Background model from smoothing $m_{4l}$ distribution from simulated samples
- Simultaneous fit performed over all categories
  - Cross-check using template method: uncertainties are ~3% smaller with per-event
Results in the 4l Channel

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

H→ZZ*→4l

- Total uncertainty of 0.37 GeV compatible with expected of 0.35 GeV
  - Main systematics from muon momentum and electron energy scale
- Combination with Run-1 reduces uncertainty further
  - Systematics are correlated, signal normalizations are not
- Result is still statistics-limited

\[ \text{Run-2: } m_H = 124.79 \pm 0.36 \ (\text{stat}) \pm 0.05 \ (\text{syst}) \]

\[ \text{Run1+2: } m_H = 124.71 \pm 0.30 \ (\text{stat}) \pm 0.05 \ (\text{syst}) \]

<table>
<thead>
<tr>
<th>Systematic effect</th>
<th>Uncertainty on ( m_{ZZ^*} ) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon momentum scale</td>
<td>40</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>26</td>
</tr>
<tr>
<td>Pile-up simulation</td>
<td>10</td>
</tr>
<tr>
<td>Simulation statistics</td>
<td>8</td>
</tr>
</tbody>
</table>
$H \rightarrow \gamma\gamma$

- Tight isolation and identification requirements for photons
- Diphoton vertex chosen using a neural network
- Events sorted into 31 exclusive categories based on properties of photons and other objects in the event
- Backgrounds from SM $\gamma\gamma$ production and jets faking photons
- Parametrized with functional form depending on category
  - Functional form for background chosen to ensure small fitted signal yield when fitting background-only samples

arXiv:1802.04146
Diphoton Mass Parameterization

- Signal in each category modeled as double-sided Crystal Ball
  - Parameters are linear functions of $m_H$
  - Obtained from simultaneous fit to simulated samples at different $m_H$ values
  - Cross-section and BR are both parametrized as function of $m_H$ as well
    - Former by production mode
Diphoton Mass Measurement

• Mass is obtained by a simultaneous fit over all categories
• Combination w/Run-1
  ▶ Signal strengths not correlated
  ▶ Part of photon energy scale systematics correlated

Run-2: $m_H = 124.93 \pm 0.21 \text{ (stat)} \pm 0.34 \text{ (syst)}$

Run1+2: $m_H = 125.32 \pm 0.19 \text{ (stat)} \pm 0.29 \text{ (syst)}$

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic uncertainty on $m_H^\gamma$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM calorimeter cell non-linearity</td>
<td>$\pm 180$</td>
</tr>
<tr>
<td>EM calorimeter layer calibration</td>
<td>$\pm 170$</td>
</tr>
<tr>
<td>Non-ID material</td>
<td>$\pm 120$</td>
</tr>
<tr>
<td>ID material</td>
<td>$\pm 110$</td>
</tr>
<tr>
<td>Lateral shower shape</td>
<td>$\pm 110$</td>
</tr>
<tr>
<td>$Z \rightarrow ee$ calibration</td>
<td>$\pm 80$</td>
</tr>
<tr>
<td>Conversion reconstruction</td>
<td>$\pm 50$</td>
</tr>
<tr>
<td>Background model</td>
<td>$\pm 50$</td>
</tr>
<tr>
<td>Selection of the diphoton production vertex</td>
<td>$\pm 40$</td>
</tr>
<tr>
<td>Resolution</td>
<td>$\pm 20$</td>
</tr>
<tr>
<td>Signal model</td>
<td>$\pm 20$</td>
</tr>
</tbody>
</table>

Not correlated

Source Systematic uncertainty on $m_H^\gamma$ [MeV]
Combined Mass Measurement

Electron and photon calibration systematics are correlated between analyses

Signal-strength parameters are left free

Photon calibration systematics are the most important

Final result compatible with Run-1 combined ATLAS+CMS measurement

Mass measured with relative uncertainty of 0.2%!

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic uncertainty in $m_H$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM calorimeter response linearity</td>
<td>60</td>
</tr>
<tr>
<td>Non-ID material</td>
<td>55</td>
</tr>
<tr>
<td>EM calorimeter layer intercalibration</td>
<td>55</td>
</tr>
<tr>
<td>$Z \rightarrow ee$ calibration</td>
<td>45</td>
</tr>
<tr>
<td>ID material</td>
<td>45</td>
</tr>
<tr>
<td>Lateral shower shape</td>
<td>40</td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>20</td>
</tr>
<tr>
<td>Conversion reconstruction</td>
<td>20</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$ background modelling</td>
<td>20</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$ vertex reconstruction</td>
<td>15</td>
</tr>
<tr>
<td>$e/\gamma$ energy resolution</td>
<td>15</td>
</tr>
<tr>
<td>All other systematic uncertainties</td>
<td>10</td>
</tr>
</tbody>
</table>
Summary

- The mass of the Higgs boson has been measured at the ATLAS detector in 36.1 fb\(^{-1}\) of 13 TeV data
- Results from the 4l and \(\gamma\gamma\) channels are compatible
- Combined Run-2 result shows a significant increase of precision over combined Run-1 result
- Combined Run-1+Run-2 result of \(m_H=124.97\pm0.24\) GeV agrees well with combined ATLAS-CMS result from Run-1
Backup
Muon Resolution and Scale
# Full H4l Event Selection

## Leptons and Jets Requirements

### Electrons
- Loose Likelihood quality electrons with hit in innermost layer, $E_T > 7$ GeV and $|\eta| < 2.47$

### Muons
- Loose identification $|\eta| < 2.7$
- Calo-tagged muons with $p_T > 15$ GeV and $|\eta| < 0.1$
- Combined, stand-alone (with ID hits if available) and segment tagged muons with $p_T > 5$ GeV

### Jets
- anti-$k_t$ jets with $p_T > 30$ GeV, $|\eta| < 4.5$ and passing pile-up jet rejection requirements

## Event Selection

### Quadruplet Selection
- Require at least one quadruplet of leptons consisting of two pairs of same flavour opposite-charge leptons fulfilling the following requirements:
  - $p_T$ thresholds for three leading leptons in the quadruplet - 20, 15 and 10 GeV
  - Maximum of one calo-tagged or standalone muon per quadruplet
- Select best quadruplet to be the one with the (sub)leading dilepton mass (second) closest the $Z$ mass
- Leading dilepton mass requirement: $50$ GeV $< m_{12} < 106$ GeV
- Sub-leading dilepton mass requirement: $12 < m_{34} < 115$ GeV
- Remove quadruplet if alternative same-flavour opposite-charge dilepton gives $m_{\ell \ell} < 5$ GeV $\Delta R(\ell, \ell') > 0.10$ (0.20) for all same(different)-flavour leptons in the quadruplet

### Isolation
- Contribution from the other leptons of the quadruplet is subtracted
- Muon track isolation ($\Delta R \leq 0.30$): $\Sigma p_T / p_T < 0.15$
- Muon calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T / p_T < 0.30$
- Electron track isolation ($\Delta R \leq 0.20$): $\Sigma E_T / E_T < 0.15$
- Electron calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T / E_T < 0.20$

### Impact Parameter
- Apply impact parameter significance cut to all leptons of the quadruplet.
- For electrons: $|d_0 / \sigma_d| < 5$
- For muons: $|d_0 / \sigma_d| < 3$

### Vertex
- Require a common vertex for the leptons

### $\chi^2$/ndof
- $\chi^2$/ndof < 6 for 4\mu and < 9 for others.
## Hγγ Reconstructed Categories

<table>
<thead>
<tr>
<th>Category</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>tH lep 0fwd</td>
<td>$N_{\text{lep}} = 1$, $N_{\text{jet}}^{\text{fwd}} \leq 3$, $N_b^{\text{tag}} \geq 1$, $N_f^{\text{fwd}} = 0$ ($p_T^{\text{fwd}} &gt; 25$ GeV)</td>
</tr>
<tr>
<td>tH lep 1fwd</td>
<td>$N_{\text{lep}} = 1$, $N_{\text{jet}}^{\text{fwd}} \leq 4$, $N_b^{\text{tag}} \geq 1$, $N_f^{\text{fwd}} \geq 1$ ($p_T^{\text{fwd}} &gt; 25$ GeV)</td>
</tr>
<tr>
<td>tH lep</td>
<td>$N_{\text{lep}} \geq 1$, $N_{\text{jet}}^{\text{fwd}} \geq 2$, $N_b^{\text{tag}} \geq 1$, $Z_{\ell\ell}$ veto ($p_T &gt; 25$ GeV)</td>
</tr>
<tr>
<td>tH had BDT1</td>
<td>$N_{\text{lep}} = 0$, $N_{\text{jet}}^{\text{fwd}} \geq 3$, $N_b^{\text{tag}} \geq 1$, BDT$_{\text{BDT1}} &gt; 0.92$</td>
</tr>
<tr>
<td>tH had BDT2</td>
<td>$N_{\text{lep}} = 0$, $N_{\text{jet}}^{\text{fwd}} \geq 3$, $N_b^{\text{tag}} \geq 1$, 0.83 &lt; BDT$_{\text{BDT2}}$ &lt; 0.92</td>
</tr>
<tr>
<td>tH had BDT3</td>
<td>$N_{\text{lep}} = 0$, $N_{\text{jet}}^{\text{fwd}} \geq 3$, $N_b^{\text{tag}} \geq 1$, 0.79 &lt; BDT$_{\text{BDT3}}$ &lt; 0.83</td>
</tr>
<tr>
<td>tH had BDT4</td>
<td>$N_{\text{lep}} = 0$, $N_{\text{jet}}^{\text{fwd}} \geq 3$, $N_b^{\text{tag}} \geq 1$, 0.32 &lt; BDT$_{\text{BDT4}}$ &lt; 0.79</td>
</tr>
<tr>
<td>tH had 4j1b</td>
<td>$N_{\text{lep}} = 0$, $N_{\text{jet}}^{\text{fwd}} = 4$, $N_b^{\text{tag}} = 1$ ($p_T^{\text{fwd}} &gt; 25$ GeV)</td>
</tr>
<tr>
<td>tH had 4j2b</td>
<td>$N_{\text{lep}} = 0$, $N_{\text{jet}}^{\text{fwd}} = 4$, $N_b^{\text{tag}} \geq 2$ ($p_T^{\text{fwd}} &gt; 25$ GeV)</td>
</tr>
<tr>
<td>VII dilep</td>
<td>$N_{\text{lep}} \geq 2$, 70 GeV &lt; $m_{\ell\ell}$ &lt; 110 GeV</td>
</tr>
<tr>
<td>VH lep High</td>
<td>$N_{\text{lep}} = 1$, $m_{c\tau} - 89$ GeV &gt; 5 GeV, $p_T^\ell + E_T^{\text{miss}} &gt; 150$ GeV</td>
</tr>
<tr>
<td>VH lep Low</td>
<td>$N_{\text{lep}} = 1$, $m_{c\tau} - 89$ GeV &gt; 5 GeV, $p_T^\ell + E_T^{\text{miss}} &lt; 150$ GeV, $E_T^{\text{miss}}$ significance &gt; 9 or $E_T^{\text{miss}} &gt; 250$ GeV</td>
</tr>
<tr>
<td>VII MET High</td>
<td>150 GeV &lt; $E_T^{\text{miss}}$ &lt; 250 GeV, $E_T^{\text{miss}}$ significance &gt; 9 or $E_T^{\text{miss}} &gt; 250$ GeV</td>
</tr>
<tr>
<td>VII MET Low</td>
<td>80 GeV &lt; $E_T^{\text{miss}}$ &lt; 150 GeV, $E_T^{\text{miss}}$ significance &gt; 8</td>
</tr>
<tr>
<td>jet BSM</td>
<td>$p_T^{j1} &gt; 200$ GeV</td>
</tr>
<tr>
<td>VII had tight</td>
<td>60 GeV &lt; $m_{jj}$ &lt; 120 GeV, BDT$_{\text{VH}} &gt; 0.78$</td>
</tr>
<tr>
<td>VII had loose</td>
<td>60 GeV &lt; $m_{jj}$ &lt; 120 GeV, 0.35 &lt; BDT$_{\text{VH}} &lt; 0.78$</td>
</tr>
<tr>
<td>VBF tight, high $p_T^{j1}$</td>
<td>$</td>
</tr>
<tr>
<td>VBF loose, high $p_T^{j1}$</td>
<td>$</td>
</tr>
<tr>
<td>VBF tight, low $p_T^{j1}$</td>
<td>$</td>
</tr>
<tr>
<td>VBF loose, low $p_T^{j1}$</td>
<td>$</td>
</tr>
<tr>
<td>ggH 2J BSM</td>
<td>$\geq 2$ jets, $p_T^{j1} &gt; 200$ GeV</td>
</tr>
<tr>
<td>ggH 2J High</td>
<td>$\geq 2$ jets, $p_T^{j1} \in [120, 200]$ GeV</td>
</tr>
<tr>
<td>ggH 2J Med</td>
<td>$\geq 2$ jets, $p_T^{j1} \in [60, 120]$ GeV</td>
</tr>
<tr>
<td>ggH 2J Low</td>
<td>$\geq 2$ jets, $p_T^{j1} \in [0, 60]$ GeV</td>
</tr>
<tr>
<td>ggH 1J BSM</td>
<td>1 jet, $p_T^{j1} &gt; 200$ GeV</td>
</tr>
<tr>
<td>ggH 1J High</td>
<td>1 jet, $p_T^{j1} \in [120, 200]$ GeV</td>
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<tr>
<td>ggH 1J Med</td>
<td>1 jet, $p_T^{j1} \in [60, 120]$ GeV</td>
</tr>
<tr>
<td>ggH 1J Low</td>
<td>1 jet, $p_T^{j1} \in [0, 60]$ GeV</td>
</tr>
<tr>
<td>ggH 0 J Fwd</td>
<td>0 jets, one photon with $</td>
</tr>
<tr>
<td>ggH 0 J Con</td>
<td>0 jets, two photons with $</td>
</tr>
</tbody>
</table>
$H \rightarrow \gamma\gamma$ Cross-checks

- BB: both photons in barrel
- BE: one photon in barrel, one in endcap
- EE: both photons in endcap
- CC: both photons converted
- UC: one photon converted, one not
- UU: both photons unconverted

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
4l Fits in Final States