Higgs physics at ATLAS

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On behalf of the ATLAS Collaboration,
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Outline

- Brief introduction and ATLAS detector
- Properties of the 125 GeV neutral scalar boson
  - Production and decay mechanisms
- Rare and Beyond Standard Model searches
  - Additional Higgs bosons, anomalous decays
- What the future holds – High Luminosity LHC
- Conclusions

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All results available on Public results page
Introduction

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~86%

~7.5% (fractions are for 13 TeV)

~4.5%

+ bbH (~1%)
Higher instantaneous luminosity in the LHC also leads to more inelastic \( p-p \) interactions per crossing (pileup) in addition to the interesting events – Challenging environment.

\[ \mathcal{L}_{\text{max}} \approx 1.4 \times 10^{34} \, \text{cm}^{-2} \, \text{s}^{-1} \]
Event display of candidate Higgs boson event in the 2µ2e final state (ZZ*) – at 13 TeV

Candidate is reconstructed in a beam crossing with 25 additionally reconstructed primary vertices from inelastic interactions.
125 GeV neutral scalar boson

- **Mass**
  - Width (< 22.7 MeV at 95% CL – via off-shell couplings) – ($\Gamma_{SM} \sim 4$ MeV) - not discussed today
  - Other models of spin-parity ruled out at > 99% CL in favour of $0^+$ (SM) – not discussed today

- **Decays to bosons and fermions**
  - Analysis cuts chosen to enhance sensitivity to different production modes
  - Not discussing Run-1 WW* and tt results

- **Coupling strengths**
  - Signal strength, $\mu$, defined as, Measurement/SM prediction

- **Will not discuss systematic uncertainty details**
  - Detector performance, e.g., jet energy scale, lepton ID, b-tagging…
  - Theory uncertainties, modelling issues, e.g., ttbb in ttH(bb)…

- **Backgrounds are analysis dependent and can be quite large**
  - Some are irreducible, e.g., WW production in H→WW*
Mass – Run-1 ATLAS/CMS

Work ongoing to make precise measurements with 13 TeV data

(ATLAS only) $m_H = 125.36 \pm 0.37 \text{ (stat.)} \pm 0.18 \text{ (syst.) GeV}$
H → γγ  \quad (\text{SM BR} \sim 0.23\%) \quad \text{Run-2} \ (13.3 \text{ fb}^{-1}): \quad \text{ATLAS-CONF-2016-067}

Events are categorized as coming from various production processes based on pt of photons, Missing transverse momentum, numbers of b-jets & leptons, leading jet pT…

- Clean experimental signature and good invariant mass resolution
- Background parametrization chosen from high statistics simulated data samples & fit to data
- Ratio of signal yield to expectation, μ = 0.85^{+0.22}_{-0.20} \ (\text{Run-2})
  - Compatible with Run-1 (where significance > 5σ)

More results available on fiducial, total and differential x-sections
H → ZZ* → 4leptons

SM BR (ZZ*) ~ 2.6%

- Clean experimental signature and good invariant mass resolution - highest S/B ratio (~2 in mass window)
  - Observed significance > 5σ in Run-1

- New event categorization (in Run-2) with respect to previous measurements

More results available on differential, fiducial and total cross-sections

σ_{tot} = 69^{+10}_{-9} ± 5 pb

LHCXSWG: 55.6 ± 2.5 pb (theory)
**Clean experimental signature**

- Proceeds via loops similar to $\gamma\gamma$ – background is $Z^+$ prompt $\gamma$, $Z$+jet (mis-id as $\gamma$)
- Event categorization to enhance sensitivity

<table>
<thead>
<tr>
<th>95%CL Upper limit</th>
<th>Expected (mu=0)</th>
<th>Expected (mu=1)</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_B/(\sigma_B)_{SM}$</td>
<td>4.4</td>
<td>5.2</td>
<td>6.6</td>
</tr>
</tbody>
</table>

**Run-2 (36.1 fb$^{-1}$)**

Our sensitivity without and with Higgs signal
Inclusive $M_{\mu\mu}$ distribution – Eight analysis regions are chosen to enrich different production mechanisms, e.g., 2 forward jets enhance VBF.

Simultaneous fit to all 8 categories in the range 110-160 GeV

Observed (expected) upper limit on $\sigma \cdot Br$ is $3.0 \ (3.1) \times$SM prediction at the 95% confidence level for a Higgs boson mass of 125 GeV.

When combined with 7 & 8 TeV data, corresponding limits: 2.8 (2.9)
H → bb (SM BR ~ 58%)  

- Since ggF and VBF production mechanisms lead to all-jet events, overwhelming multi-jet (QCD) background  
- VH process has better sensitivity i.e., in association with a W or Z  
  - Look at WH and ZH, where Z → νν, ℓℓ and W → ℓν, with 2 b-tag jets  
    - Analysis validated with (W/Z) Z (→ bb) [Signif: 3.0 (3.2)]  
- H → bb also used in search for Higgs produced in association with top quark pairs (later)

Run-2 (13.2 fb⁻¹): ATLAS-CONF-2016-091

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Observed (expected) Significance: 0.4σ (1.9σ)

Run-1 ATLAS + CMS: Obsvd. (expected) signif. for H → bb: 2.6 (3.7)
H→ bb

- New analysis that probes VBF production mechanism
  - Use high-pT central photon to reduce multi-jets (there is also destructive interference in background)

An irreducible, non-resonant background also present
Use multi-variate techniques to discriminate

- Observed (expected) upper limit of 4.0 (6.0^{+2.3}_{-1.7})x the SM prediction
  - Comparable to Run-1

Run-2 (12.6 fb^{-1}): ATLAS-CONF-2016-063
ttH – many final states

(\sigma \sim 0.5 \text{ pb at 13 TeV})

Run-2 (13.2-13.3 \text{ fb}^{-1})

• Each of the analyses is quite complex – irreducible backgrounds, modelling issues, systematic uncertainties
• Heavy use of multi-variate techniques to discriminate signal from background
• Categorize events based on top-quark decays, # leptons, # of jets and b-jets…

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**ttH**

Run-2 (13.2-13.3 fb⁻¹)

multi-leptons
ttH Combination

Run2 (13.2-13.3 fb⁻¹): ATLAS-CONF-2016-068
One way to combine is based on the analysis of five production processes: ggF, VBF, WH, ZH and ttH, and five decay modes: $H \rightarrow \gamma\gamma$, WW, ZZ, $\tau\tau$, and bb (out of 25 independent parameters, 2 are fixed to SM values)

(H$\rightarrow$bb in ggF/VBF)

(Not enough sensitivity for ttH/WH/ZH in H$\rightarrow$ZZ)

Results are for $\sigma_i.B^f$ relative to SM values
Searches for Rare and BSM signatures
H → φγ

- Decay probes coupling of Higgs to strange quark
  - SM prediction is very small ~ 2.3*10^{-6}
  - Rate can be enhanced in some BSM models (MFV, RS, Composite pseudo-Goldstone…)

- Corresponding Z decay provides a benchmark and a test of SM
  - Prediction is (1.17±0.08)*10^{-8}

- φ → K⁺K⁻

<table>
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<tr>
<th>Branching Fraction Limit (95% CL)</th>
<th>Expected</th>
<th>Observed</th>
</tr>
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<tbody>
<tr>
<td>B(H → φγ) [ 10^{-3} ]</td>
<td>1.5^{+0.7}_{-0.4}</td>
<td>1.4</td>
</tr>
<tr>
<td>B(Z → φγ) [ 10^{-6} ]</td>
<td>4.4^{+2.0}_{-1.2}</td>
<td>8.3</td>
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Di-Higgs searches

- Non-resonant & resonant di-Higgs in bbbb, γγbb, γγWW* modes

Destructive interference

Via BSM particles

Can also modify SM loops

In SM, measure of trilinear self coupling, \( \lambda_{HHH} \)

Run-2 (10.1-13.3 fb\(^{-1} \)): ATLAS-CONF-2016-049

(Non-resonant) \( \sigma \cdot Br < 29 \times \) SM prediction

\(< 330 \text{ fb} \) \( (11.3^{+0.9}_{-1.0} \text{ fb}) \)

Randall-Sundrum model (resonant)
SM (higgs) → γγ + Missing transverse momentum

M(Z_B') from 1-2000 GeV, M(DM) from 1-1000 GeV
Z_B' decays to Dirac fermionic DM candidates

M(Z'_B) = 200 GeV, m(DM) = 1 GeV

For m(DM) = 1 GeV, M(Z'_B) > 850 GeV

Direct stop production with H or Z

Run2 (36.1 fb⁻¹): ATLAS-CONF-2017-019

(1-2) lep+ ≥4 b-jets designed for \( \tilde{t}_2 \rightarrow h + \tilde{t}_1 \)
or \( \tilde{\chi}_2 \rightarrow h + \tilde{\chi}_1 \)

Other signal regions with ≥ 3 lep + ≥ 1 b-jet

\( \tilde{t}_2 \) and \( \tilde{t}_1 \) > 870 GeV at 95% CL
High mass resonance searches

Searches are ongoing:
- All final states are being looked at: $\gamma\gamma$, $Z\gamma$, $\tau\tau$, $ZZ$, $WW$, $WZ$, $Zh$, $tt$

Other ongoing searches
- $H^+ \rightarrow tb, \tau\nu$
- $H^{++}$
- LFV decays
- Decays to 4 b-quarks via 2 new spin-0 particles
- Decays to dark photons
- …
The future – High Luminosity LHC

Simulation of $t\bar{t}$ event with pileup = 200
- **Shutdown for Phase-1 upgrade starts 2019 - recommence data-taking in 2021 at 14 TeV**
  - \( \mathcal{L} \sim 2-3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \). Collect \( \sim 300 \text{ fb}^{-1} \) by 2023

- **Shutdown for Phase-2 upgrade in 2024, recommence in 2026 (HL-LHC)**
  - \( \mathcal{L} \sim 7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \), \( \int \mathcal{L} \geq 3000 \text{ fb}^{-1} \)
  - Expected pileup \( \sim 200 \) (compared to < 50 now)
  - Major upgrade of ATLAS, e.g., replace inner tracking system, expected to have increased coverage, \( |\eta| < 4 \) (in contrast to current \( |\eta| < 2.5 \))
  - Many benefits, e.g., b-tagging for forward jets, mitigate background from pileup, improved lepton identification, better resolution in missing transverse momentum
  - Impact on important physics channels, e.g., di-Higgs, VBF \( H \rightarrow WW^* \ldots \)
  - From past experience, analyses usually get smarter once we have data
Outlook

- Comprehensive program of studying the 125 GeV neutral scalar boson
  - Many more Run-1 and Run-2 results available on our public page

- Current datasets are ~ 1% of what we hope to collect in the future

- Looking forward to another successful run in 2017
  - Stable beams as of yesterday!