Latest Higgs Physics Results from the ATLAS Experiment

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Higgs boson

Discovery of the Higgs boson is a milestone in understanding electroweak symmetry breaking.

In the Standard Model of particle physics, at high energies electroweak symmetry is unbroken and fundamental particles are massless.

The non-zero vacuum expectation value of the Higgs field spontaneously breaks electroweak symmetry.

Higgs boson: positive parity, zero spin, zero electric and colour charge

- Through the Higgs mechanism the W and Z bosons acquire mass
- Fermions (quarks and leptons) acquire mass through Yukawa interaction
Higgs production and decay

gg fusion (gg→H) \(\sim 87\%\)  
vector boson fusion (VBF) \(\sim 7.2\%\)  
associated vector boson (VH) \(\sim 5\%\)  
associated top-antitop (ttH) \(\sim 0.6\%\)

Dominant decay mode:  
b-quark pair, large multijet background

Golden channel:  
ZZ \(\rightarrow\) 4 leptons (e, \(\mu\))
Higgs boson discovery

- First observation of a new particle reported on 4\textsuperscript{th} July 2012

- Paper showed 5.9\sigma excess in H->ZZ*->4l, H->WW*, H->\gamma\gamma decays (using ~11fb @ 7 and 8 TeV)

ATLAS Higgs Physics Program includes:
- Search for Higgs boson in every channel, and in rare decays

- Probe Higgs properties:
  - Higgs mass and width
  - Higgs spin and parity
  - Strengths of couplings to bosons and fermions
  - Differential cross-section
  - Off-shell couplings and width

- Use Higgs as a tool to probe BSM Physics
Results covered in this talk:

- Latest and greatest Higgs mass and width measurements
- Higgs spin and couplings measurement
- Direct evidence of Higgs coupling to fermions (H-> ττ)
- Higgs searches in association with top quark; probe of top-Higgs Yukawa coupling
- Fiducial and differential cross-section measurements (H->γγ, H->ZZ*->4l)
The Large Hadron Collider (LHC) is 27km in circumference and 100 m underground. It accelerates beams of Protons (Hadrons) near to the speed of light and collides them at vast energies in the center of particle detectors.
ATLAS detector

- Muon chambers
- Toroid magnets
- Solenoid magnet
- Transition radiation tracker
- Semiconductor tracker
- Pixel detector
- LAr electromagnetic calorimeters
- LAr hadronic end-cap and forward calorimeters
- Tile calorimeters

44m
25m
ATLAS Performance

- Proton-proton collision data 4.5 (20.3) fb$^{-1}$ collected by ATLAS at 7 (8) TeV in 2011 (2012)

- Data taking efficiency 94%

- Electron/muon ID performance almost independent of pile-up conditions
Higgs Mass and Width
Improved mass measurement

PRD 90, 052004 (2014)

- Improved measurement of the Higgs boson mass in decay channels H-> γγ and H-> ZZ* -> 4l

- Golden Channel: H ->ZZ(*) -> 4l
  - Small σ x BR ~ 2.9 fb (@ 8TeV)
  - High (S/B ~ 2:1) (dom. ZZ)
  - Excellent mass resolution (1.6 (2.2) GeV in 4µ (4e) channel)

- H -> γγ
- Good γ/e ID (75% purity after cuts)
- Excellent mass resolution (~1.7GeV)
- Syst. dominated Eγ scale

ATLAS

H → ZZ* → 4l

1s = 7 TeV: ∫Ldt = 4.5 fb⁻¹
1s = 8 TeV: ∫Ldt = 20.3 fb⁻¹

Events / 2.5 GeV

Data
Signal (m_h = 124.5 GeV μ = 1.66)
Background ZZ*
Background Z+jets, t†
Systematic uncertainty

m_{4l} [GeV]

Mass measurement categories

s/b weighted sum

ATLAS

Data
Combined fit:
- Signal+background
- Background
- Signal

Σ weights - fitted dev

m_{γγ} [GeV]
Improved mass measurement

Combined fit to reconstructed invariant mass spectra of decay channels H-> γγ and H-> ZZ* -> 4l

- Higgs produces narrow mass peak in these channels
- Experimental resolution 1.6 – 2 GeV
- Improved electromagnetic energy calibration (photons, electrons)
- Reduction in the muon momentum scale uncertainty

$m_H = 125.36 \pm 0.37 \text{ (stat)} \pm 0.18 \text{ (syst) GeV}$

- 0.3 % precision measurement
- Systematic uncertainty reduced by factor ~ 3
- 2.0 $\sigma$ compatibility between channels
High mass (> 2m_Z) off-peak regions of Higgs→ ZZ signal sensitive to off-shell Higgs boson

New physics could alter how Higgs interacts with other particles in high mass region

High mass H→ ZZ → 4l & 2l2#nu channels used for **off-shell signal strength** and constraints on Γ_H

Off-shell (on-shell) signal strength μ_{off-shell (on-shell)} in high mass region > 2m_Z threshold:
Limits on the off-shell Higgs boson signal strength set using a binned maximum likelihood fit to the Matrix Element (ME)-based discriminant

Combining channels assuming same on/off shell couplings Theo. $\Gamma_H = 4.2$ MeV$^1$

Improved sensitivity to total width with combined measurements than with direct measurement, under set of strict assumptions

$\mu_{\text{off-shell}} < 6.7$ (7.9 (exp.))

$\mu_{\text{off-shell}} < 11.3$ (2\ell 2\nu)

$\Gamma_H/\Gamma_H^\text{SM} < 5.7$ (8.5 (exp.))
Higgs Spin and Couplings
Higgs spin and parity


Spin and parity measured from angular distributions of decay products

\( J^P = 0^+ \) hypothesis compared with alternative hypothesis

\( ZZ^* \rightarrow 4l, H \rightarrow WW^* \rightarrow ll\nu\nu, H \rightarrow \gamma\gamma \) decay mode

\( J^P = 0^-, 1^+, 1^-, 2^+, 2^- \) excluded > 95% CL

Results consistent SM predictions

Evidence for spin-0 nature of Higgs

\[ H \rightarrow \gamma\gamma \]

\[ H \rightarrow ZZ^* \rightarrow 4l \]

\[ H \rightarrow WW^* \rightarrow e\nu\nu\mu\nu \]

\[ f_{\psi} (%), J^P = 0^-, J^P = 1^+, J^P = 1^-, J^P = 2^+ \]
Measurement of overall signal strength $\mu = \sigma / \sigma_{\text{SMH}}$

Combination $\mu = 1.30 \pm 0.12 \text{(stat)} ^{+0.14}_{-0.11} \text{(sys)}$.

Cross-section ratio $\mu_{\text{VBF+VH}} / \mu_{\text{ttH+ggF}} = 1.4^{+0.7}_{-0.5}$

Providing evidence for VBF production at $4.1\sigma$ level
Higgs decay into fermions
First preliminary evidence for Higgs decay into fermionic states, probe Higgs Yukawa couplings to fermions

- VBF + boosted (ggF) and VH process Higgs production
- $\text{BR}(H \rightarrow \tau^+ \tau^-) \approx 6.3\%$
- 3 channels: ($\tau_{\text{lep}}, \tau_{\text{lep}}$) ($\tau_{\text{lep}}, \tau_{\text{had}}$) ($\tau_{\text{had}}, \tau_{\text{had}}$)

Tau lifetime $\approx 2.9 \times 10^{-13}$

- Hadronic decays $\approx 65\%$
- Leptonic decays $\approx 35\%$
Signal is extracted from Boosted Decision Tree (BDT) distributions

Excess observed (expected) with signal significance $4.1\sigma$ ($3.2\sigma$)

Signal compatible with a Higgs boson mass of 125 GeV

ATLAS Preliminary

$m_{\ell\ell} = 125$ GeV

$H \rightarrow \tau\tau$

- Signal strength $\mu = 1.4^{+0.5}_{-0.4}$
Top Associated Higgs Production
Constraints on top-Higgs Yukawa coupling

Higgs production in association with top quarks $ttH$

- Observation will provide direct measurement of $tH$ Yukawa Coupling $Y_t^{SM}$

  Important to understand EW symmetry breaking

  Excellent probe for New Physics

- Analysis involves complex final states, large backgrounds (inclusive top production)

- ATLAS considered two Higgs decay modes:
  - $tt H \rightarrow bb$ (ATLAS-CONF-2014-011)
  - $tt H \rightarrow \gamma\gamma$ and combination (ATLAS-CONF-2014-043)

Top decays almost 100% to W-boson and b-quark

Final state dependant on decay of W-boson
Constraints on top-Higgs Yukawa Coupling

- ttH(bb) channel
- Semileptonic and Dileptonic Channels considered
- Sensitivity improved by categorising events according to jet and b-tagged jet multiplicities.

Fractional contribution to total background prediction

**ATLAS** Preliminary Simulation

<table>
<thead>
<tr>
<th>Signal-rich regions</th>
<th>Signal-depleted regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>m_H = 125 GeV</td>
<td></td>
</tr>
<tr>
<td>S/B = 0.1%</td>
<td>S/B = 0.2%</td>
</tr>
<tr>
<td>S/B = 0.2%</td>
<td>S/B = 0.4%</td>
</tr>
<tr>
<td>S/B = 0.4%</td>
<td>S/B = 0.9%</td>
</tr>
<tr>
<td>S/B = 1.3%</td>
<td>S/B = 2.3%</td>
</tr>
<tr>
<td>S/B = 3.8%</td>
<td></td>
</tr>
</tbody>
</table>

Neural Networks trained to separate signal from top background based on event shape and kinematics.
Constraints on top-Higgs Yukawa coupling

**ATLAS-CONF-2014-011**

- Multivariate technique used to discriminate between signal and background (tt+jets dominated) in signal-enhanced regions
- No significant excess above background expectations
- Observed (expected) 95% C.L. limit of 4.1 (2.6) times SM cross-section obtained

**ATLAS** Preliminary

\[
\text{Events/bin} \quad \begin{cases} 
10^5 & (\text{Data 2012}) \\
10^4 & (ttH (\mu_{st}=1.7)) \\
10^3 & (ttH (\mu_{95\% \text{ excl.}}=4.1)) \\
10^2 & (\text{Bkgd}) \\
10^1 & (\text{Comb. Single lepton and Dilepton}) \\
10^0 & (\text{Data / Bkgd}) \\
10^{-1} & (\text{log}_{10}(S/B)) \\
10^{-2} & (\text{L} = 20.3 \text{ fb}^{-1}) \\
10^{-3} & (\text{L} = 8 \text{ TeV})
\end{cases}
\]

**ATLAS** Preliminary

- Dilepton: 2.9 ± 2.3 (1.4)
- Lepton+jets: 1.3 ± 1.6 (0.8)
- Combination: 1.7 ± 1.4 (0.7)

best fit \( \frac{\sigma}{\sigma_{\text{SM}}} \) for \( m_{H} = 125 \text{ GeV} \)
 Constraints on top-Higgs Yukawa coupling

**ATLAS-CONF-2014-043**

**t(t)H(γγ) Channel**

- Higgs in association with single top also sensitive to $Y_t^{SM}$

- Unbinned signal+bg likelihood fit to mass spectra used to estimate number of events from bg and SM Higgs

- No excess observed, upper limit $6.5 \times \sigma_{SM} \times BR(H->γγ)$

- Lower (upper) limits set on top-Higgs Yukawa coupling field strength parameter at 95% CL, as $-1.3 \pm 8.1$

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**Obs. (exp.) upper limit on $\mu$ is 5.6 (3.9)**
Constraints on top-Higgs Yukawa Coupling

Likelihood fit performed to data in 19 categories from two analyses yield signal strength

- Observed (expected) significance is 1.5 (1.0) $\sigma$

$$\mu_{t\bar{t}H} = 1.6 \pm 0.6 \text{ (stat.)} \pm^{+1.1}_{-1.0} \text{ (sys.)}$$

- Observed (expected) 95% CL upper limit on $t\bar{t}H$ production is 3.9 (2.3) x SM value

ATLAS-CONF-2014-043

$t(t)H(\gamma\gamma)$ and $ttH$ bb combination

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Primordial QCD Matter 2014

Kate Shaw
Fiducial and Differential Cross-Section
Fiducial and differential Higgs cross-section

- $H \rightarrow \gamma\gamma$ channel, measurement sensitive to new physics
- Signal yield is extracted in each fiducial region using a fit to $m_{\gamma\gamma}$ spectrum

$$\sigma_{\text{fid}}(pp \rightarrow H \rightarrow \gamma\gamma) = 43.2 \pm 9.4 \text{ (stat.)} ^{+3.2}_{-2.9} \text{ (syst.)} \pm 1.2 \text{ (lumi)} \text{ fb.}$$

- Twelve differential cross-sections are measured within baseline fiducial volume
- Probe of Higgs boson kinematics, properties and associated jet activity
- No significant deviation from SM prediction is observed
Fiducial and differential Higgs cross-section

arXiv:1407:4222 accepted JHEP

- H→ ZZ* → 4l decay channel, differential cross-section measurements sensitive new physics
- Signal yield extracted in fiducial volume by a template fit to the 4 lepton mass spectrum

$$\sigma_{\text{tot}}^{\text{fid}} = 2.11^{+0.53}_{-0.47} \text{(stat.)} \pm 0.08 \text{(syst.)} \text{ fb.}$$

- Differential cross-sections measured for 6 kinematic variables
- No significant deviation from SM prediction is observed
Summary

- Entering era of precision Higgs physics, Higgs is a tool to probe for BSM physics
- More Run I results being finalised, and Run II is just around the corner!
- More data needed to observe the Higgs in further channels, such as associated top and bb and $\mu\mu$ decay
The ATLAS Collaboration

~3000 scientists
38 countries